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A joint modeling project with scientists from the U.S.A. and U.S.S.R. has been accomplished. The three geographical areas investigated include Lake Baikal and the Sea of Azov in the U.S.S.R. and Saginaw Bay, Lake Huron in the U.S.A. The modeling approaches ranged from those employing material and mass conservation to describe water movement to those involving solution of the complete three-dimensional hydrodynamic equations. The model calculations were compared to available data and, in all cases, reasonable agreement was obtained.

This report covers a period from May 1977 to December 1977, and work was completed as of April 1978.

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RESULTS OF A JOINT U.S.A./U.S.S.R. HYDRODYNAMIC AND TRANSPORT MODELING PROJECT

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FOREWORD

The Environmental Research Laboratory - Duluth is concerned with the effects of pollutants on freshwater ecosystems, particularly the Laurentian Great Lakes. The development and verification of mathematical models describing the transport and fate of pollutants in freshwater ecosystems are carried out at the Large Lakes Research Station at Grosse Ile, Michigan.

This report describes a modeling effort accomplished under the Lakes and Estuaries Project of the U.S.A./U.S.S.R. Agreement on Cooperation in the Field of Environmental Protection. Models developed by scientists in one country were applied to aquatic systems in the other country and compared to existing data. The accomplishments of these researchers demonstrate the utility of joint scientific collaborations between countries.

Donald I. Mount, Ph.D.
Director
Environmental Research Laboratory
Duluth, Minnesota

PREFACE

The U.S.A./U.S.S.R. Agreement on Cooperation in the Field of Environmental Protection was first signed in 1972 and has just recently been renegotiated. Eleven areas of cooperation were enumerated, ranging from air and water pollution to legal aspects. As a result of this agreement, hundreds of scientists and engineers from the two participating countries have made exchange visits.

This present work was accomplished under the auspices of Project 02.02-12, Protection and Management of Water Quality in Lakes and Estuaries, of the Environmental Agreement. The intent of the authors in undertaking this particular work was to provide a contact between researchers in the two countries who were involved in describing and modeling various aspects of the processes in large bodies of water. It was also our desire to do a modeling project whereby scientists from both countries could work together, each providing some part of their expertise for the benefit of the project. We think that we have accomplished this and hope that others will think so also. We would like readers of this report to keep in mind that this work was initiated and completed in a relatively short period of time compared to the normal frame of time for a scientific project. This work did not encompass all that we had originally intended. We realize that it was more important for us to show how scientists from our two countries could work together on a definite project rather than to make sure we completed everything. Since this was just an initial modeling effort, many areas could not be covered in as much detail as one would have liked. Hopefully, the modeling efforts between the scientists of our two countries will be continued in the near future and the fruits of these joint undertakings will be an increase in the credibility of the use of modeling in the aquatic environment.

ABSTRACT

A joint modeling project with scientists from the U.S.A. and U.S.S.R. has been accomplished. The three geographical areas investigated include Lake Baikal and the Sea of Azov in the U.S.S.R. and Saginaw Bay, Lake Huron in the U.S.A. The modeling approaches ranged from t ose employing material and mass conservation to describe water movement to those involving solution of the complete three-dimensional hydrodynamic equations. The model calculations were compared to available data and, in all cases, reasonable agreement was obtained.

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SECTION 1

INTRODUCTION

The United States of America (U.S.A.) and Union of Soviet Socialist Republic (U.S.S.R.) are confronted with many environmental problems which can affect the health and welfare of their respective societies. Expanding populations and industries, and increasing urbanization and farming have resulted in alterations to the hydrosphere and to changes in loads of waste materials which effect the quality of the environment. The mutual concern for the environment provided the impetus for the U.S.A./U.S.S.R. Agreement on Cooperation in the Field of Environmental Protection signed in 1972 (Appendix A).

As part of the Agreement, Project 02.02-12, Protection and Management of Water Quality in Lakes and Estuaries, was initiated. Although the two nations share no common boundaries on any lake or estuary, they do share a common concern for water quality preservation, and the need to understand the physical, chemical, and biological processes that effect and determine water quality. To share scientific knowledge on limnological processes, a joint modeling project was initiated during the exchange visit by Soviet representatives to the U.S.A. in 1976.

In June 1977, Dr. Tudor T. Davies from U.S. Environmental Protection Agency (EPA), Environmental Research Laboratory, Gulf Breeze, Florida, and Dr. John F. Paul and Mr. William L. Richardson from EPA, Large Lakes Research Station, Grosse Ile, Michigan, visited the Institute of Mechanics and Applied Mathematics, Rostov State University, Rostov-on-Don, U.S.S.R. They met with Drs. A.A. Zenin, A.A. Matveyev, A.B. Gorstko and F.A. Surkov. During this visit, the details of the joint modeling project were arranged, and a project report outline prepared. As a first step, it was agreed to compare formulations and results of hydrodynamic and transport models developed by the two groups. The objective was to provide a basis for further verification of lakewide and nearshore hydrodynamic and transport models.

It was agreed that three geographical areas and three model formulations would be investigated. The areas are:

1. Lake Baikal (U.S.S.R.) with special emphasis on the Selenga River plume
2. Saginaw Bay, Lake Huron (U.S.A.)
3. Sea of Azov (U.S.S.R.)

The three modeling approaches are:

1. Hydrodynamic modeling using conservation equations for mass, energy, and momentum as developed by Dr. Paul
2. Transport modeling using mass conservation as developed by Drs. Gorstko and Surkov, referred to as type 1
3. Transport modeling using conservation of material and water mass as applied to Saginaw Bay by Mr. Richardson, referred to as type 2

Approaches 1 and 2 would be applied to Lake Baikal and to the Sea of Azov, and approaches 2 and 3 to Saginaw Bay. The model results were to be compared to availabe data, and if possible, to each other. The result of this would provide additional verification for the models, and determine whether or not refinements were necessary.

This report provides a general background summary on each of the 3 water bodies, followed by a synopsis of the mathematical models used. The applications of these models and comparisons with available data are then presented. The appendices provide reference materials for those unfamiliar with the U.S.A./U.S.S.R. Environmental Agreement, additional background on Lake Baikal and the Sea of Azov, detailed results of the hydrodynamic and dispersion calculations summarized in the main report, and data for the Selenga shallows region of Lake Baikal in May-June 1976. Appendices B, C, and D appear in a separate volume, which is available from National Technical Information Services (NTIS).

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The results of the model calculations were compared to available data and, in all cases, reasonable agreement was obtained.

It was shown that the hydrodynamic model calculation for the Sea of Azov could be useful in assessing the effects of hydrologic modifications.

The results of the work completed under this project, including comparisons between U.S.A. and U.S.S.R. models and comparisons to field data, have permitted the participants to make an initial determination of the degree of agreement and validity of the existing hydrodynamic and transport models.

This work represents a preliminary step in a possible comprehensive comparison of modeling methodology in the two countries among researchers for both hydrodynamic and biochemical models. It is hoped this project will lead to further cooperation among modelers of both countries.

A more detailed comparison of models will require a continuing commitment by both nations, as well as by the individual modelers. The time required for the present study was about one month, with two weeks spent in each country.

It may be desirable to continue this type of work through the International Institute of Applied Systems Analysis (IIASA) in Laxenburg, Austria. The total time required would be on the order of one to two years, with periodic exchange visits to IIASA by the persons involved.

SECTION 3

LAKE BAIKAL

BACKGROUND OF LAKE BAIKAL AND SELENGA RIVER REGION

The basin of Lake Baikal is located almost centrally in Asia, in a very rugged mountain province in south Siberia, the Baikal Region. The characteristic geomorphological features of the region include medium and high mountain ranges extending over 1500 km in the southwest to northeast direction, and an alternation of ridges and trenches, the largest of which is filled with waters of the lake.

Lake Baikal is the oldest and deepest intracontinental body of water in the world. The formation of the Baikal trench began about 30 million years ago. The watershed area of the lake is 0.54 million km^2, and the area of the lake itself is 31.5 thousand km^2. The length of the lake is 636 km; maximum width, 79 km; minimum width, 25 km; maximum depth, 1620 m; and volume of the water mass, about 23 thousand km^3. The topography of the lake is shown in Figure 1. The trench of Lake Baikal is divided into three basins, of which the middle one is the deepest. It is separated from the southern basin by the Selenga shallows, a delta formed by the lake's largest tributary, the Selenga River. The contribution of the Selenga amounts to about 50% of the total runoff into the lake. Table 1 provides an annual average water balance for the lake (Vikulina and Kashinova 1973).

TABLE 1. ANNUAL AVERAGE WATER BALANCE FOR LAKE BAIKAL DURING THE PERIOD 1901-1970 (km^3/year)

Inflow		Outflow	
Precipitation	9.29	Runoff to Angara River	60.39
Condensation on lake surface	.82	Evaporation	10.77
River inflow	58.75		
Groundwater inflow	2.30		
Total	71.16	Total	71.16

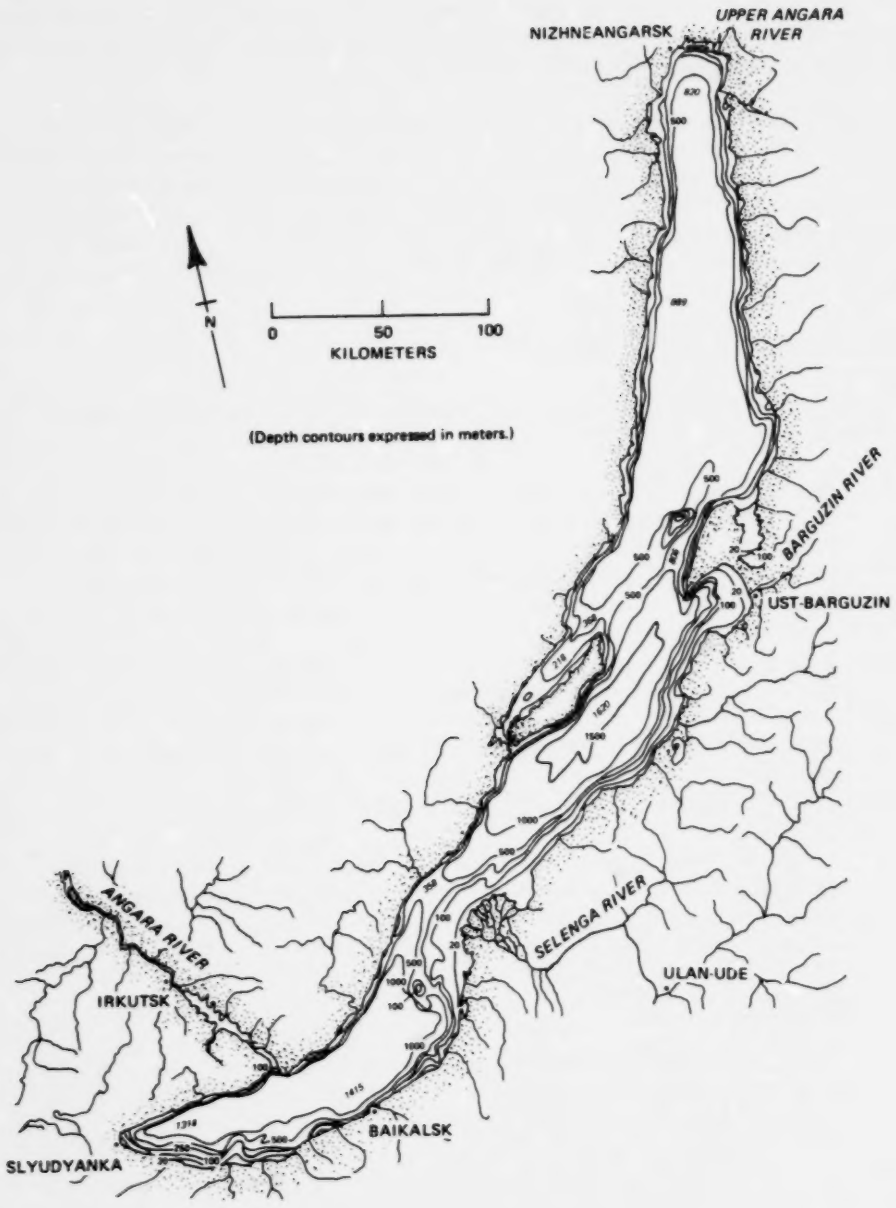


Figure 1. Lake Baikal.

Lake Baikal contains approximately 4/5 of the total surface water reserves of the U.S.S.R. However, the importance of the lake does not end there. During the past approximately 1 million years, when this body of water was formed in its present boundaries, special characteristics were developed: low solute content, high transparency, low temperature, and high saturation with dissolved oxygen.

Lake Baikal's ecosystem is distinct and closely balanced. In the course of its evolution, its organisms have adapted to conditions varying little with time, and have reacted very sensitively to changes in these conditions. Indicative of this sensitivity is the fact that organisms of the open deepwater parts of the lake do not dwell in the shallow regions near the delta, which are subjected to the action of the river runoff.

EXPERIMENTAL DATA AND METHODS

Limnological measurements in Lake Baikal are made by a number of agencies and institutes in the U.S.S.R. These include:

1. Hydrochemical Institute of the Main Administration of the Hydrometeorological Service of the U.S.S.R. (hydrochemistry)
2. State Hydrological Institute of the Main Administration of the Hydrometeorological Service of the U.S.S.R. (hydrology)
3. Irkutsk Administration of the Hydrometeorological Service of the U.S.S.R. (hydrology and meteorology)
4. Trans-Baikal Administration of the Hydrometeorological Service of the U.S.S.R. (hydrochemistry and hydrology of the Selenga River)
5. Limnological Institute of the Siberian Branch of the U.S.S.R. Academy of Sciences (hydrobiology, hydrology, and chemistry of sedimentation)
6. Irkutsk State University (hydrobiology)

The relevant data for this report, summarized below, are the meteorology, current measurements, temperature, transparency, and concentration of suspended solids. A description of these data for Lake Baikal and the shallows of the Selenga River is provided in Appendix B.

Whole Lake Circulation

The primary cause of water movement in Lake Baikal is the wind. In localized areas, like the Selenga River shallows, an appreciable influence is also exerted by inertial forces formed by large inflows. In the central and southern regions of the lake, northwesterly winds predominate (31% of the time on an annual basis). Near the eastern shore of southern Baikal, strong southeasterly winds are frequent. The wind speed distribution is approximately the same for all directions on an annual basis. The mean speeds are 5-10 m/sec, but speeds of 16-20 m/sec occur during the spring-summer period.

Several types of circulation patterns are formed by the wind. Six or seven large scale cyclone-type spirals have been observed in all three basins. Within these, there are several mesoscale eddies and secondary circulations, particularly in regions with heterogeneous bottom topography and shoreline morphometry.

The currents throughout the lake have an annual variation. They increase with intensification of winds after the lake is cleared of ice in May and June, decline during the calmer summer periods, and increase during the autumn storm period. The observed average speed of the large scale circulation is about 2-3 km per day (2.3-3.5 cm/sec) during the navigation season, and 1-1.5 km per day (1.1-1.8 cm/sec) during the ice free period. Large scale gusts an order of magnitude higher have been observed over short periods.

In the nearshore region (8-10 km from shore), the currents are almost uniformly directed over the vertical column. The currents do vary with distance from shore, e.g., the currents at a distance of 0.4 to 0.6 km from shore are 1.5 to 2 times lower than those at a distance of 1.5 to 2 km. Steady longshore currents begin to appear about 1.5 to 2.5 km (Aybund 1973). At 2-3 km, the currents are 1.5 to 2 times lower than at 3 to 5 km. In the deepwater, the maximum observed current speeds appear at 25 to 50 m depth. The magnitude of the currents then decreases to the 100 m depth, below which the currents become almost homogeneous in both magnitude and direction. According to observations in southern Lake Baikal during the navigation period, average current speeds are in the range of 12-18 cm/sec at 15 m depth, and 4-8 cm/sec at 50 m and below.

The vertical variation of the current structure is determined to a considerable degree by the temperature stratification in the water. During stratification, the deepwater parts of the lake separate into three zones: 1) the upper (dynamically active), 2) the deep, and 3) the bottom zone. The upper zone includes 30% of the total depth and is characterized by large current speeds with highly variable current direction. In the deep zone, the currents change little with time and in speed. The bottom zone, not including the bottom friction layer, is characterized by a slight increase in current magnitude.

During the cold season, the currents remain but their speed is much reduced. A major part of the time (60%), the magnitude of the currents under the ice is less than 2 cm/sec. However, in areas located far from the shore, speeds of 5-9 cm/sec that persist for 5-12 days have been recorded.

Circulation in the Selenga River Shallows

The Selenga River is the largest tributary of Lake Baikal. The drainage area composes 83.4% of the lake runoff area, and the river inflow amounts to 50% of the total runoff into the lake. The topography of Selenga River Shallows is shown in Figure 2. The distribution of the river

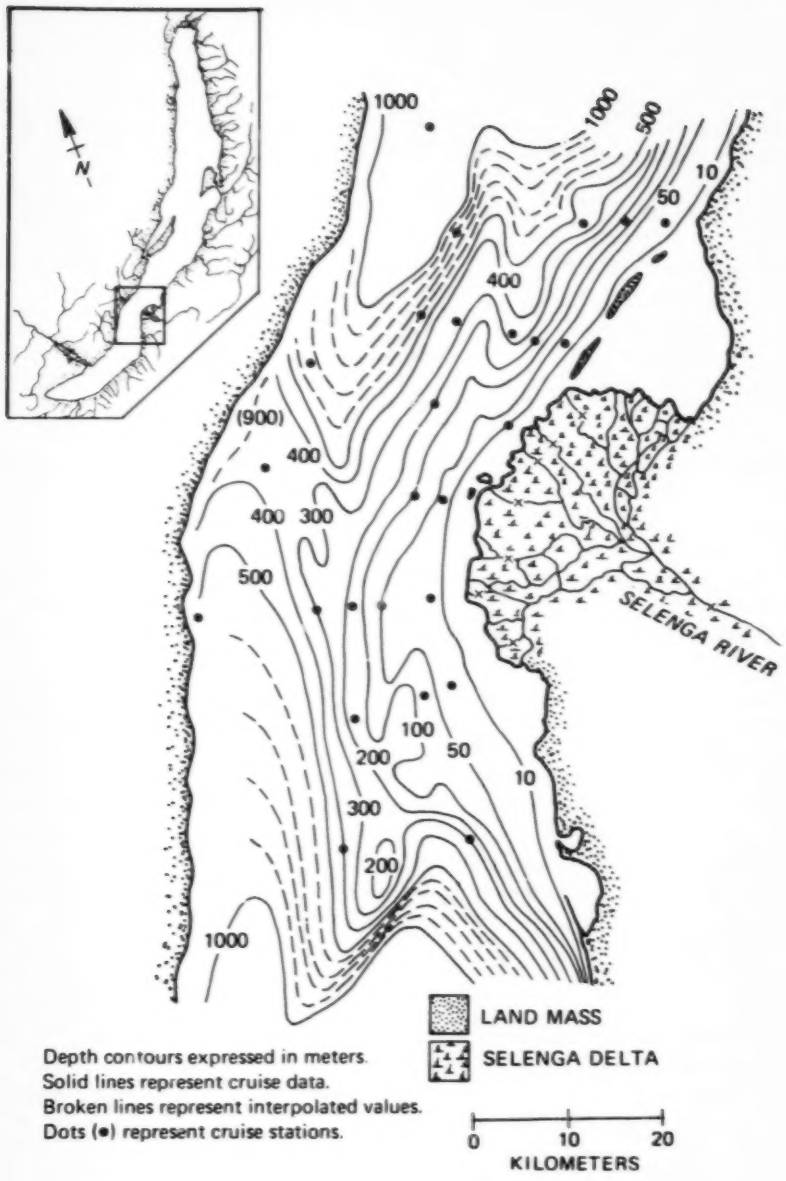


Figure 2. Selenga River Region of Lake Baikal.

water into the lake takes place in a system of numerous delta branches, numbering up to 30 during high river flow. The distribution of the river water through these branches is highly variable, but mostly depends on time of year and river flow. The speed of the entering river water varies from 6 cm/sec to 70 cm/sec, with penetration of the water into the lake varying from .3-.4 km to 9 km.

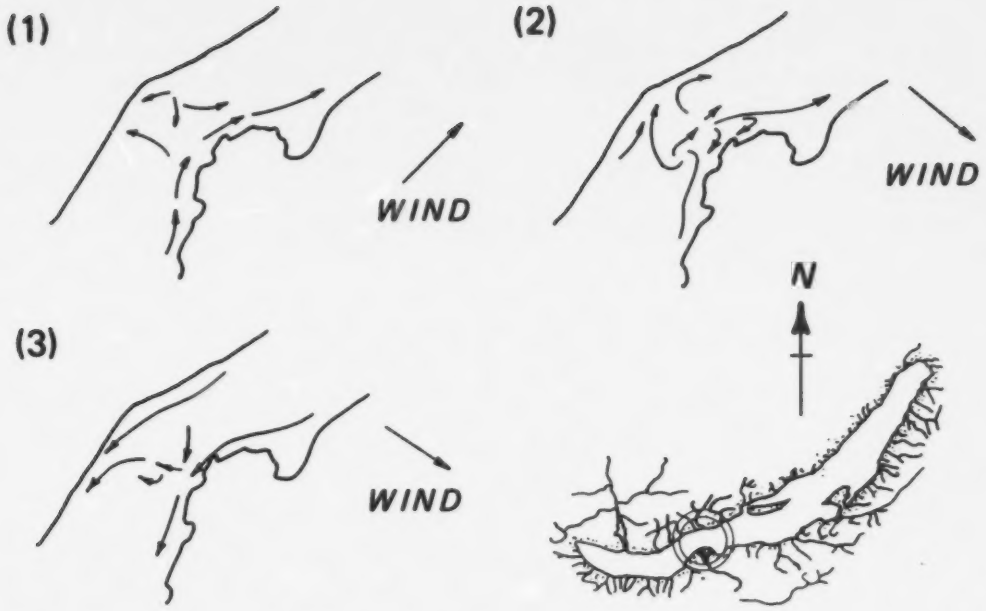
The distribution of the Selenga River water, once it enters the lake, is highly dependent upon the local wind field. During southwesterly winds, the river water has been detected along the eastern and northeastern shore of the lake at up to 130 km. In the presence of northeasterly winds, the river water is transported to the region south of the delta. Examples of observed surface currents and their short-term variation in the Selenga River Shallows region are shown in Figure 3. It should be noted that the current patterns are dependent on the perseverance of the wind from a particular direction.

PROBLEMS TO BE ADDRESSED

Of particular importance to the existing and future water quality of the lake as a whole, and to the Selenga River area in particular, is the Selenga River basin. Anthropogenic factors influence the character of the Selenga River and its chemical runoff. It is hoped that rational efforts and sound measures will be undertaken to preserve a healthy ecosystem, and, at the same time, allow for economic development of the Baikal region. The planned development in the lake basin from 1971 to 2000 will amount to over 10 billion rubles (13.6 billion dollars), with approximately 6% of this amount spent on environmental protection. During the next 30 years, a 4 to 5-fold increase in gross industrial production, 3-fold increase in agricultural production, and 1.5-fold increase in timber production are anticipated. In addition, the population is expected to increase by a factor of 1.5 during this same period. Most of these increases will be centered in two regions: 1) the basin along the course of the Selenga River southwest of the lake, and 2) along the Baikal-Amur railway under construction in the area north of the lake.

The importance of the Selenga River Region, and of the shallow zone encircling it, can be related to the growth and development of the Selenga whitefish young in this area. After the larvae have hatched in April and May, the whitefish remain in the delta for 35-45 days, and in the shallows until mid-August. Hence, until the end of June, the whitefish young are influenced directly by chemical runoff, and during the subsequent period are exposed to its influence in the diluted shallow waters. If the level of toxic pollutants in the water of the Selenga River from April to August is detrimental to these fish, there is no doubt that it can have an even stronger influence on the remaining trophic links in this region of the lake.

One objective of this U.S.A./U.S.S.R. joint modeling project is to attempt to describe the circulation and transport characteristics of Lake Baikal for the whole lake, and for the Selenga River Shallows area using



(1) Prevailing southwesterly wind (30 Aug 1972).
(2) Prevailing northwesterly wind (31 Aug 1972).
(3) Steady lasting northwesterly wind (8 Sep 1972).

Figure 3. Observed surface currents in the Selenga River Region of Lake Baikal.

mathematical models. Combined with the existing knowledge of transport and circulation obtained from a qualitative description of experimental data, a better understanding of cause and effect relationships should be obtained. This could eventually lead to the construction of more detailed biochemical models for management purposes. In addition, this analysis may provide experimentalists with new insights for data observation.

SECTION 4

SAGINAW BAY

BACKGROUND OF SAGINAW BAY

Saginaw Bay was formed about five thousand years ago following the final retreat of the Pleistocene Ice and recession of Lake Saginaw. The bay remains as a shallow arm of Lake Huron, having an average depth of 5 m, a width of 42 km at its mouth, a minimum width of 21 km, and a length of 82 km from Saginaw River to the mouth (Figure 4).

Although small in size compared to all of Lake Huron, the bay is an important water resource to the State of Michigan and the Great Lakes Region of the United States. Its surface area of about 2960 km^2, shoreline of 230 km, and volume of 300 million cubic meters serves a variety of water uses. Saginaw Bay is illustrative of a high water-use requirement from a water body of degraded quality that resulted from municipal and industrial inputs and from runoff of agricultural and urban land.

Historically, Saginaw Bay has been one of the more productive commercial fishing areas in the Great Lakes. Even today, the bay has the highest fish productivity of the entire Lake Huron ecosystem. The fishing industry was established in the early 1800's and reached a peak in 1902 with 6,432,000 kg production. Since the 1930's, production and types of fishes have been so severely altered that, in 1966, the production reached an ebb of 1,160,000 kg.

In addition to water supply, commercial fishing, and waste assimilation, the bay provides for extensive recreational uses including boating, fishing, and swimming. Also, the bay is an important navigational waterway for commercial vessels with foreign exports totaling over 7 million metric tons. This shipping, however, requires a navigation channel to be dredged through the inner bay and up the Saginaw River. Over 380,000 cubic meters of spoil are removed annually, some of which are disposed of in the bay.

The bay receives the waste discharges and runoff from a drainage basin serving over 1.2 million people (1970). Over 50% of the basin is farm land, 34% forest, 3.5% urbanized, and 1.2% is recreational land. Products of the basin include sugar beets, beans, corn, wheat, dairy and livestock. Industrial products include food, automobiles, chemicals, and lumber. These activities contribute large amounts of waste materials to the bay as reflected by the material loads measured at the tributary mouths.

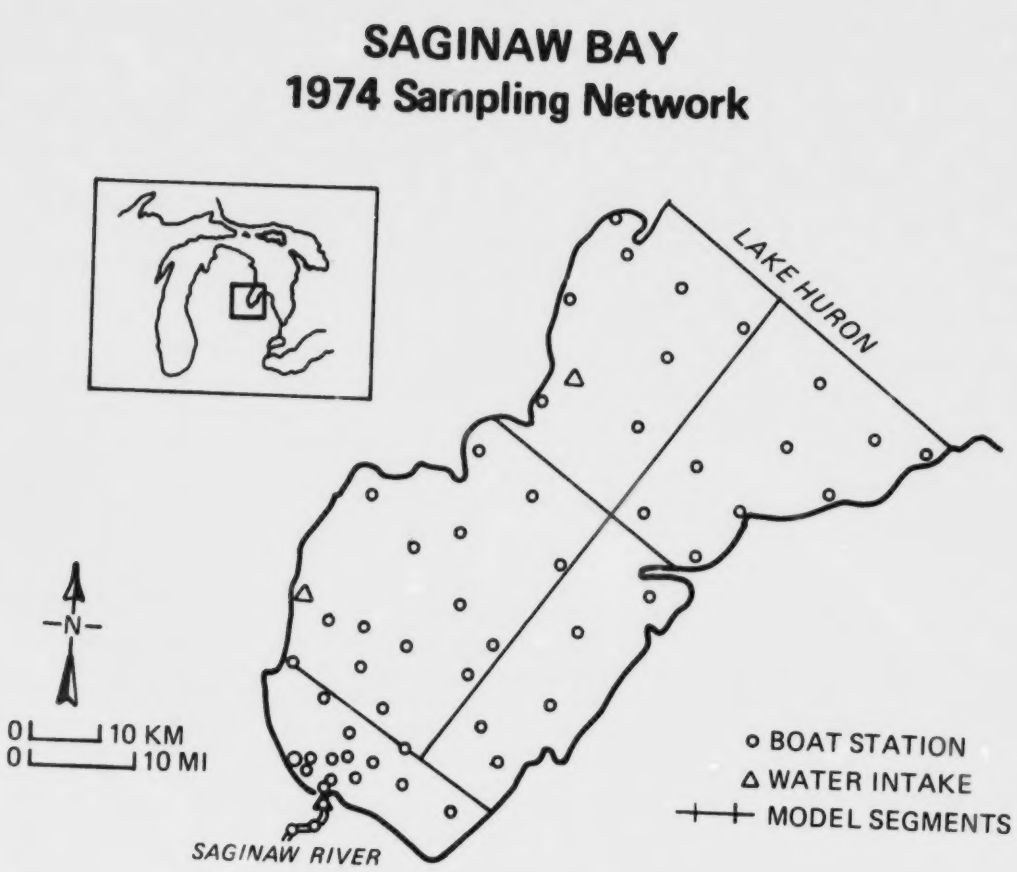


Figure 4. Saginaw Bay, including 1974 sampling network.

EXPERIMENTAL DATA AND METHODS

The U.S. Environmental Protection Agency, Large Lakes Research Station (LLRS) at Grosse Ile, Michigan, has sponsored surveys of water quality in the bay since 1974 (Smith et al. 1977). The surveys have been conducted to: 1) establish a water quality baseline, 2) provide data for modeling biochemical processes and dynamics, and 3) provide a comprehensive document for the International Joint Commission (IJC) Upper Lakes Reference Study.

Location of sampling stations are indicated in Figure 4. During 1974-75, 30 cruises (Table 2) were conducted by the Cranbrook Institute of Science in support of and in conjunction with several other organizations. Each survey was conducted over a 3-day period by two vessels. The analytical methodology used for each water quality parameter is summarized in Table 3. Quality control procedures were incorporated into the laboratory program. All data were processed and stored in the EPA STORET system, a water quality data base system.

The data for 1974 to 1976 were analyzed for the IJC Water Quality Board using one way analysis of variance to determine the existence of discernible trends. The bay was divided into 5 segments of unique characteristics and the data grouped and averaged for each segment. In general, the analysis revealed increases in the inner bay, Segment 2, for chlorophyll a, total phosphorus, and total Kjeldahl nitrogen (see Figure 5). The data indicates that enrichment of the bay has increased during the period 1974-1976.

PROBLEMS TO BE ADDRESSED

The primary water quality problems determined in Saginaw Bay are enrichment and the resultant problems associated with overabundance of algae, particularly taste and odor in municipal water supplies. Historically, total dissolved solids (chlorides) from solution mining in the basin have been a primary concern in the bay. In the 1960's, chlorides were recorded at over 100 mg/l near the Saginaw River. Control programs implemented in the 1970's have reduced present values to about 40 mg/l. More recent water quality problems relate to toxic substances detected in fishes in the bay.

To adequately manage water quality in this complex environment, LLRS has undertaken a research program to develop an understanding of cause and effect relationships involved with these water quality problems. Bierman (1976) has developed a multispecies eutrophication model for the bay. DiToro and Matystik (1976) have calibrated a chlorophyll a phytoplankton biomass model, Canale and Squire (1976) have developed a steady state phosphorus and chloride transport model, and Richardson (1974 and 1976) has calibrated and verified a steady-state chloride transport model and calibrated a time variable chloride transport model. All of these models depend heavily on a quantification of the net circulation in the bay over a particular time scale. The steady-state models use a time average of several weeks to a season, whereas the time variable models require suitable resolution over the entire annual biological growth cycle.

TABLE 2. SAGINAW BAY CRUISE SCHEDULE FOR 1974-75

Cruise/survey	Sampling dates	No. stations sampled	Satellite pass dates
Cruise 1	11/5-7/73	37	10/31-11/1/73
Cruise 2	12/3-4/73	41	12/5 & 6/73
Cruise 3	2/18-21/74	16	2/15 & 16/74
Cruise 4	3/25/74	7	3/23 & 24/74
Cruise 5	4/16-20/74	44	4/10 & 11/74
Cruise 6	4/28-30/74	59	4/28 & 29/74
Cruise 7	5/13-17/74	51	5/16 & 17/74
Cruise 8	6/2-5/74	47	6/3 & 4/74
Cruise 9	6/18-22/74	59	6/21 & 22/74
Cruise 10	7/8-10/74	59	7/9 & 10/74
Cruise 11	7/25-27/74	59	7/27 & 28/74
Cruise 12	8/25-27/74	59	9/1 & 2/74
Cruise 13	9/18-20/74	59	9/19 & 20/74
Cruise 14	10/6-8/74	58	10/7 & 8/74
Cruise 15	11/11-14/74	36	11/12 & 13/74
Cruise 16	12/16-18/74	23	12/18 & 19/74
Cruise 17	2/17-19/75	33	2/20 & 21/75
Cruise 18	3/18/75	15	3/27 & 28/75
Cruise 19	4/9-11/75	30	4/1 & 2/75
Diurnal Survey (Sta. 56)	4/28-29/75	1	
Cruise 20	4/30-2/75	37	5/1 & 2/75
Cruise 21	5/20-22/75	37	5/19 & 20/75
Diurnal Survey (Sta. 56)	6/2-3/75	1	
Cruise 22	6/5-8/75	32	6/6 & 7/75
Cruise 23	6/25-27/75	37	6/24 & 25/75
Diurnal Survey (Sta. 56)	7/11-12/75	1	
Cruise 24	7/13-16/75	37	7/12-13/75
Cruise 25	7/29-31/75	36	7/30-31/75
Diurnal Survey (Sta. 56)	8/16-17/75	1	
Cruise 26	8/18-20/75	37	8/17 & 18/75
Cruise 27	9/3-5/75	37	9/4 & 5/75
Diurnal Survey (Sta. 56)	9/21/75	1	
Cruise 28	9/23/75	19	9/22 & 23/75
Cruise 29	10/9-11/75	37	10/10 & 11/75
Diurnal Survey (Sta. 56)	10/25-26/75	1	
Cruise 30	10/27-29/75	29	10/28 & 29/75
Cruise 31	11/16-18/75	35	11/15 & 16/75
Cruise 32	12/16/75	9	12/21 & 22/75

TABLE 3. ANALYTICAL METHODOLOGY FOR SAGINAW BAY WATER QUALITY PARAMETERS

Parameters	Where measured: in situ	Where measured: on ship	Where measured: at LLRS	Max. time to analysis	Methods	Equipment/ instrumentation
Temperature	X	X		(in situ)	Submerged thermistor probe; termometry	Martek Mark II Monitor
Oxygen, dissolved	X			(in situ)	Submerged KCl probe	Martek Mark II Monitor
Specific conductivity		X		10 min.	Electric conductance measurement	Beckman RC19 Conductivity Bridge
Chloride, filtered			X	48 hrs.	Ferric thiocyanate color reaction	Technicon AA2 Auto Analyzer
pH	X	X		10 min.	Submerged combination pH probe	Martek Mark II Monitor Fisher 520 pH/Ion Meter
Akalinity, total		X		10 min.	Sulfuric acid (0.02N) titration to pH 4.5	Burette & Fisher 520 pH/Ion Meter
Secchi disc depth	X			(in situ)	Visual estimation	9 cm diam. B & W disc
Chlorophyll a, non-filterable			X	4 wks.	Extraction & spectrophotometry (SCOR/UNESCO)	P-E Coleman 124 Double Beam Spectrophotometer
Carbon, filt. organic			X	2 wks-sealed 7 mos-analyzed	Sealed ampuole wet oxidation & IR analysis	Oceanography International 052413 & MSA 300 IR analyzer
Carbon, unfilt. organic			X	2 wks-sealed 7 mos-analyzed	Sealed ampuole wet oxidation & IR analysis	Oceanography International 052413 & MSA 300 IR analyzer
Solids, unfilt. total			X	2 wks.	Gravimetric measurement	Mettler H10 Balance
Silicates, filt. reactive			X	48 hrs.	"Molybdenum blue" color reaction	Technicon AA2 Auto Analyzer
Ammonia, filtered total			X	48 hrs.	Berthelot color reaction	Technicon AA2 Auto Analyzer
Nitrate + Nitrite, filt.			X	48 hrs.	Sulfanilimide (diazo) color reaction	Technicon AA2 Auto Analyzer
Nitrogen, unfilt. Kjeldahl			X	48 hrs.	Digestion & autoanalysis for ammonia	Heating Block and Technicon AA2 Auto Analyzer
Phosphates, filt. reactive			X	48 hrs.	"Phospho-molybdenum blue" color reaction	Technicaon AA2 Auto Analyzer
Phosphorus, filt. total			X	48 hrs.	Digestion & autoanalysis for phosphate	Heating Block and Technicon AA2 Auto Analyzer
Phosphorus, unfilt. total			X	48 hrs.	Digestion & autoanalysis for phosphate	Heating Block and Technicon AA2 Auto Analyzer
Sodium, unfiltered			X	6 mos.	Flame Atomic Absorption Spectrophotometry (undigested)	Instrumentation Laboratory 353 AA Spectrophotometry
Potassium, unfiltered			X	6 mos.	Flame Atomic Absorption Spectrophotometry (undigested)	Instrumentation Laboratory 353 AA Spectrophotometry
Calcium, unfiltered			X	6 mos.	Flame Atomic Absorption Spectrophotometry (undigested)	Instrumentation Laboratory 353 AA Spectrophotometry
Magnesium, unfiltered			X	6 mos.	Flame Atomic Absorption Spectrophotometry (undigested)	Instrumentation Laboratory 353 AA Spectrophotometry

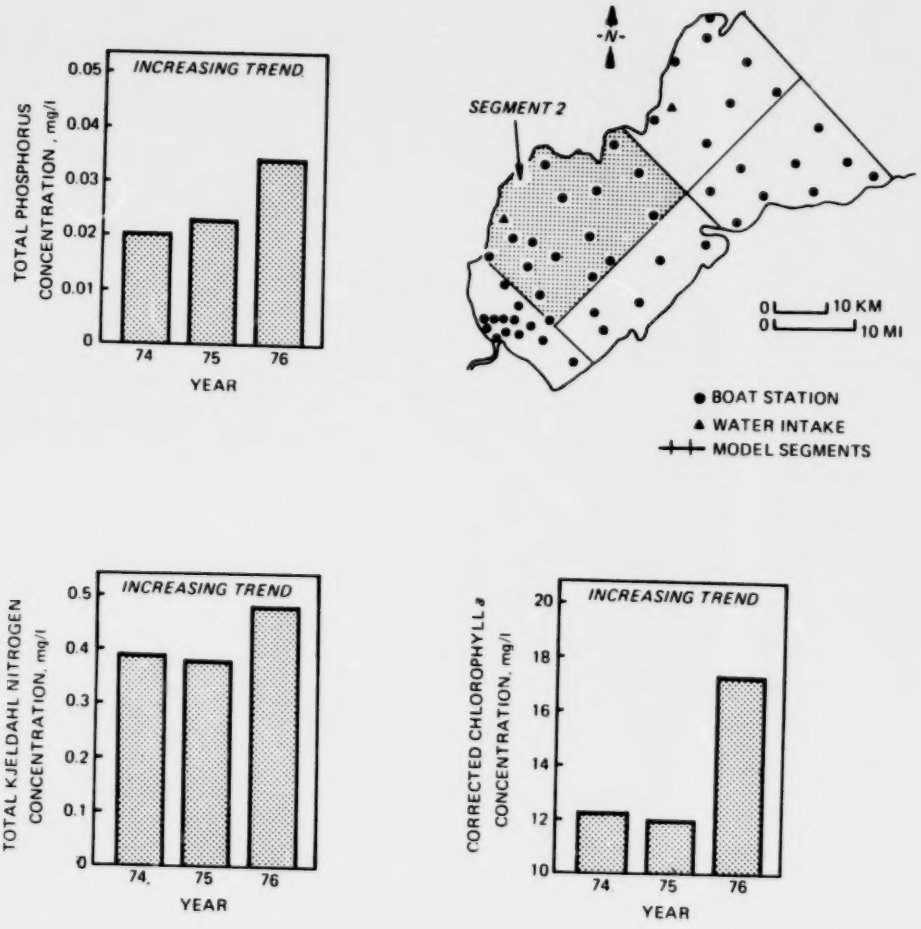


Figure 5. Inner Saginaw Bay, Segment 2, water quality for 1974-1976.

The problem to be addressed in this report is that of describing chloride transport in Saginaw Bay as a method of quantifying circulation patterns.

SECTION 5

SEA OF AZOV

BACKGROUND OF SEA OF AZOV

The Sea of Azov is a comparatively small body of water located between 45° and 47° N latitude, and 35° and 39° E longitude (Figure 6). Its area is 38,000 km^2, and the volume is about 320 km^3. The Sea of Azov is shallow. Its maximum depth is approximately 13 meters, with an average depth of about 8 meters.

The sea is an important source of fish protein and, thus, is an important resource to the Rostov Region of the U.S.S.R. One hundred and four species of fish have been identified in the bay, nine of which comprise 90% of the fish biomass. Also, 332 phytoplankton species, 155 zooplankton species, and 180 benthos species have been identified.

Large quantities of materials from the Sea of Azov drainage basin and hydrological modifications on the major rivers have had considerable impact on water quality, and subsequent effects on biological processes. The most common pollution components are oxygen demanding materials (BOD), wastes from petroleum production, phenolic compounds, detergents, pesticides, and nutrients. The content of heavy metal salts in the pelagic zone of the sea are at the level of the natural geochemical background.

A much more serious impact may result, however, if a barrier is constructed between the Black and Azov Seas, as has been proposed. The purpose of a barrier would be to reduce the salinity influx from the Black Sea. However, this may have a deleterious impact on the Sea of Azov. One purpose of modeling the Sea of Azov is to predict the consequences of such potential modifications. However, before predictions can be made, it is necessary to calibrate and verify models for existing conditions. For this report, only the hydrodynamic and transport components of the model formulation will be considered, and only the hydrological and meteorological data will be discussed. More details on the Sea of Azov are presented in Appendix B.

EXPERIMENTAL DATA AND METHODS

One of the key processes in the Sea of Azov is the water exchange between various parts of the sea and the associated redistribution of the solutes, suspensions, and organisms. The dynamics of the seawater are

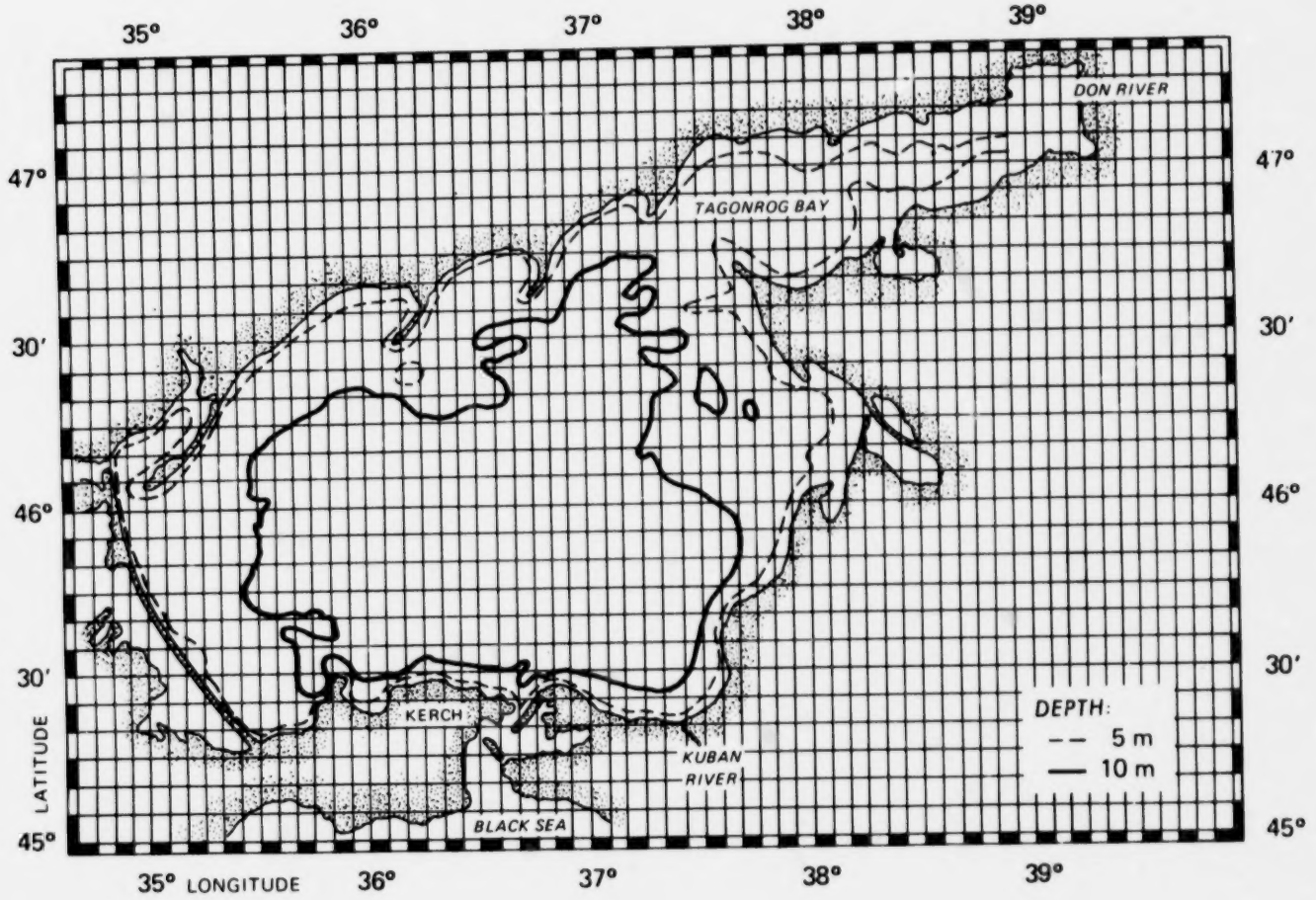


Figure 6. Sea of Azov.

essentially determined by the wind, and the horizontal water exchange is determined by the wind-generated system of currents. Typical of the Sea of Azov is the short time lag of the process. Because of the shallowness of the sea and unstable wind conditions, the speed and direction of currents can change very rapidly.

According to the data in the Hydrometeorological Handbook for the Sea of Azov (Anonymous 1972), wind-generated currents of 2-10 cm/sec have the highest frequency (up to 60%). Currents with speed of 10-20 cm/sec, corresponding to winds of 5-10 m/sec, have a frequency of about 30%. The maximum currents do not exceed 60-80 cm/sec. Some observations of currents during the summer of 1957 are shown in Figure 7. Parameters relevant to these currents are listed in Table 4.

During the cold half of the year, easterly winds prevail. Their frequency during this period amounts to 45-50%, and the frequency of westerly winds, about 30%. The wind speed during the fall and winter periods reaches an average maximum of 6-7 m/sec. Storms with easterly winds of over 10-15 m/sec also occur at that time.

In spring and summer, the wind patterns change. The frequency of westerly winds increases to 38-45% and that of easterly winds decreases to 25-30%. Later (July - August), the wind speed drops to the annual minimum, which amounts to a long-term average of 4.2 m/sec. During the course of a year, the frequency of northerly and southerly winds does not usually exceed 10%, and the frequency of calms is approximately 7%.

In addition to wind, the following factors also contribute to the dynamics of the sea: runoff, atmospheric precipitation, evaporation, and water exchange with the Black Sea through the Kerch Straits. Data on a long-term average water balance are listed in Table 5.

TABLE 5. AVERAGE WATER BALANCE FOR SEA OF AZOV
(km^3/year)

Gain		Loss	
Inflow from river	41	Evaporation	36
Precipitation	14	Outflow to Black Sea	51
Inflow from Black Sea	32		
Total	87	Total	87

The water exchange between the Sea of Azov and Black Sea is the most variable component of the water balance. During the period of observation, the maximum annual outflow through the straits was 67.1 km^3 (1932) and the minimum was 38.8 km^3 (1950). The extremes of annual inflow from the Black Sea were 38.1 km^3 (1950) and 28.9 km^3 (1932), while the extremes of net water exchange were 38.1 km^3 (1932) and 0.7 km^3 (1950).

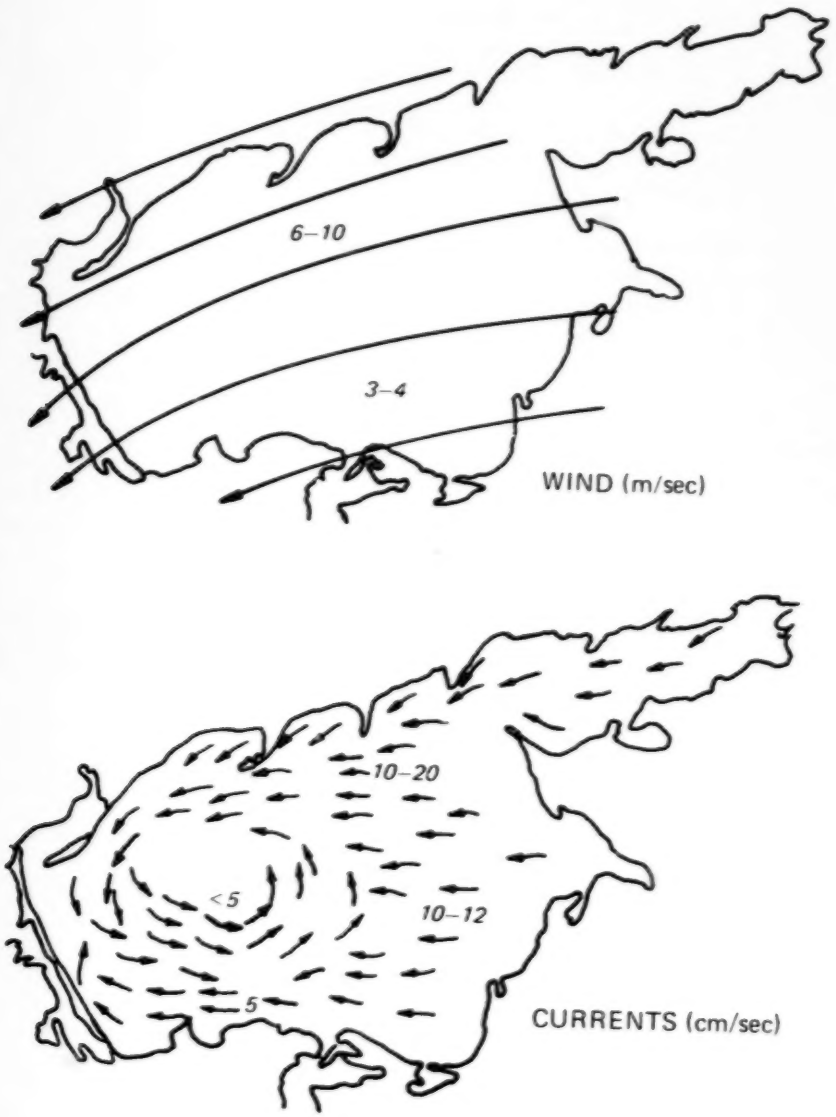


Figure 7a. Observed currents in Sea of Azov during Summer of 1957.

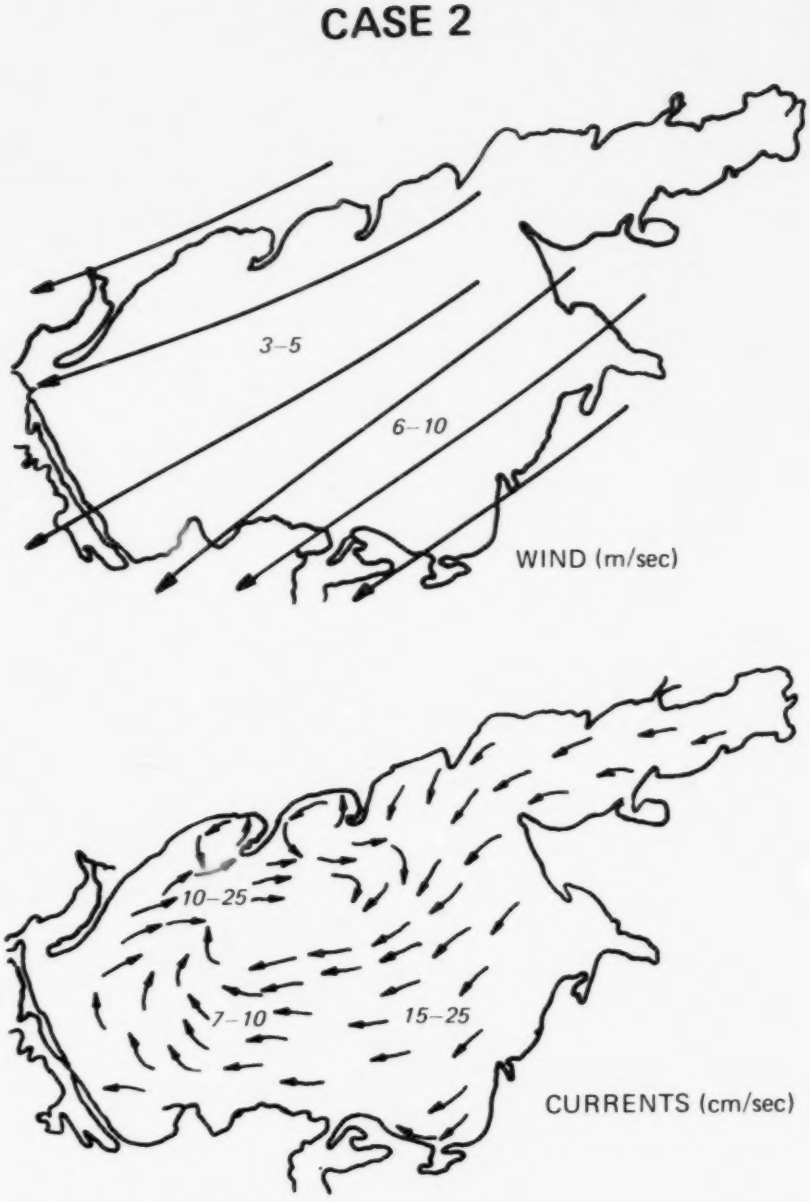


Figure 7b. Observed currents in Sea of Azov during Summer of 1957.

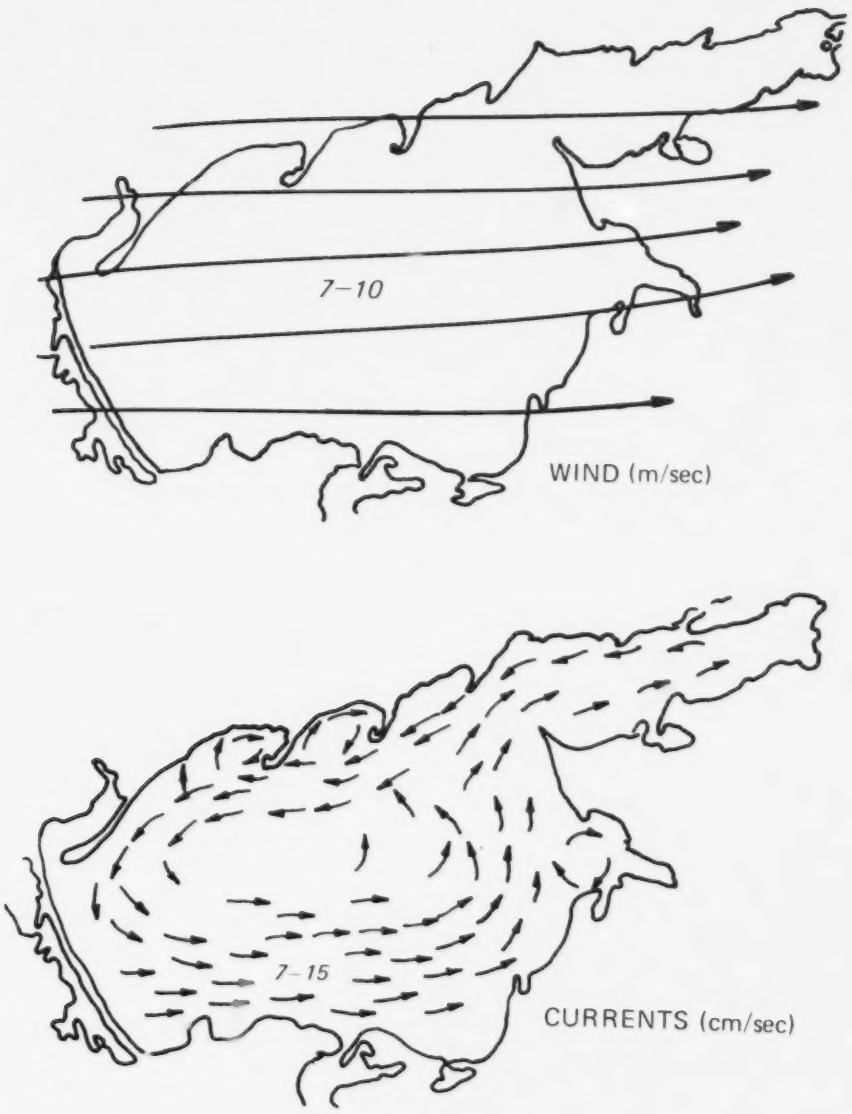


Figure 7c. Observed currents in Sea of Azov during Summer of 1957.

TABLE 4. PARAMETERS OF INFLOW/OUTFLOW FOR SEA OF AZOV DURING SUMMER OF 1957

Parameters specific to current observations				Average parameters for the summer 1957 (km^3/month)			
	Case 1	Case 2	Case 3		June	July	August
Don river flow (m^3/sec)	530	600	570	Flow from Sea of Azov to Black Sea	2.9	1.4	1.4
Kuban river flow (m^3/sec)	500	520	450	Flow from Black Sea to Sea of Azov	2.0	4.6	3.2
Evaporation (mm/day)	2.4	2.0	2.8	Net flow out of Sea of Azov	.9	-3.2	-1.8
Precipitation (mm/day)	0	0	0.4				

A systematic study of the hydrometeorological regime of the Sea of Azov began in 1922. Up to that time, only periodic measurements had been made. In connection with projects to regulate the runoff of the Don and Kuban Rivers during 1949, a number of scientific and planning institutes carried out additional studies that made it possible to prepare forecasts of possible changes in the hydrological regime of the sea. Observations made up to 1959 were classified and correlated in the Hydrometeorological Handbook for the Sea of Azov (Anonymous 1972). At the present time, the Azov Scientific Research Fishery Institute, the chief organization engaging in comprehensive investigations of the Azov ecosystem, routinely conducts four cruises per year in April, July, August, and October.

PROBLEMS TO BE ADDRESSED

A considerable portion of the catchment basin of the Sea of Azov is located in a zone of insufficient precipitation. For this reason, the river runoff is very limited, amounting to an average of 41 km^3 (Gorstko 1976). The bulk of the runoff is due to two rivers, the Don and the Kuban (27.9 and 13.9 km^3 annual contribution, respectively). The exceptional variability of the Don River inflow with time (52 km^3 in 1942 and 11.8 km^3 in 1950) causes large fluctuations in the total water reserves of the basin. The river runoff of the Azov Basin is used for the needs of industry, agriculture, power engineering, water transport, municipal water supply and fisheries. The Sea of Azov is the closing link in the utilization of the water. It follows from general ecological considerations that the effects of anthropogenic action in the basin should accumulate in the ecosystem of the Sea of Azov. This is indeed the case (Gorstko and Surkov 1975).

The principal problem areas for the Sea of Azov created by man are the following:

1. Irreversible removal of a considerable part of the runoff
2. Seasonal leveling out of river drainage
3. Reduction in the breeding areas of migratory and semimigratory fishes resulting from the difficulty of access to spawning grounds
4. Change in biogenic and mineral runoff

The state of natural equilibrium of the Sea of Azov ecosystem has already been disturbed by man's activities and is now in an intermediate state. The direction of future anthropogenic activity within the Sea of Azov basin is an unresolved issue. Several alternative approaches are possible. A modeling framework for the entire ecosystem is underway at the Institute of Mechanics and Applied Mathematics, University of Rostov. It is anticipated that the modeling efforts will influence management decisions that will be made for the basin.

One objective of this U.S.A./U.S.S.R. joint modeling project is to describe the hydrodynamic and material transport characteristics of the sea. It is hoped that this work will provide a basis to be used in assessing the alternative approaches for future activity within the basin.

SECTION 6

MATHEMATICAL MODELS

HYDRODYNAMIC MODEL

This effort is composed of two components: the basic hydrodynamic calculation and the transport of dissolved and/or suspended material. Each component will be discussed separately.

Summary of Hydrodynamic Component

The equations for the hydrodynamic component are derived from the time-dependent, three-dimensional equations for conservation of mass, momentum, energy, and salinity. The principal assumptions used are:

(a) The pressure is assumed to vary hydrostatically.
(b) The rigid-lid approximation is made, i.e., the vertical velocity at the undisturbed water surface is assumed to be a constant value. The assumed constant value is usually zero. This approximation is used to eliminate surface gravity waves and their associated small time scales, greatly increasing the maximum allowable time step in the numerical computations. For applications where evaporation and/or precipitation are important, an appropriate non-zero value is used.
(c) Eddy coefficients are used to account for the turbulent diffusion effects. The horizontal coeffficients are assumed to be constant, but the vertical coefficients are assumed to be some function of the local dependent variables.

The resulting equations are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial y} + f_o v = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(A_H \frac{\partial u}{\partial x}\right)$$

$$+ \frac{\partial}{\partial y}\left(A_H \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V \frac{\partial u}{\partial z}\right), \tag{2}$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z} - f_o u = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(A_H \frac{\partial v}{\partial x}\right)$$

$$+ \frac{\partial}{\partial y}\left(A_H \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_H \frac{\partial w}{\partial z}\right) \qquad (3)$$

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = \frac{\partial}{\partial z}\left(B_H \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(B_H \frac{\partial T}{\partial y}\right)$$

$$+ \frac{\partial}{\partial z}\left(B_V \frac{\partial T}{\partial z}\right) \qquad (4)$$

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = \frac{\partial}{\partial z}\left(B'_H \frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(B'_H \frac{\partial S}{\partial y}\right)$$

$$+ \frac{\partial}{\partial z}\left(B'_V \frac{\partial T}{\partial z}\right), \qquad (5)$$

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = g, \qquad (6)$$

$$\rho = f(T,S), \qquad (7)$$

where

x,y = horizontal coordinates,

z = vertical coordinate,

u,v = fluid velocities in x and y directions,

w = fluid velocity in z-direction,

t = time,

p = pressure,

T = temperature,

S = salinity,

ρ = density,

f_o = Coriolis parameter,

A_H = horizontal eddy viscosity,

A_V = vertical eddy viscosity,

ρ_o = density at reference conditions,

B_H = horizontal eddy conductivity,

B_V = vertical eddy conductivity,

B'_H = horizontal eddy diffusivity for salinity,

B'_V = vertical eddy diffusivity for salinity,

g = gravitational acceleration, and

$f(T,S)$ = equation-of-state.

Before the above equations are put into appropriate finite-difference form, they are transformed by a stretching of the vertical coordinate. With such a transformation, the same number of vertical grid points can be present in the shallow as in the deeper parts of the water body. This ensures that in the shallow areas there is no loss of accuracy in the computations due to lack of vertical resolution. The transformation is:

$$x \leftrightarrow x,$$
$$y \leftrightarrow y,$$
$$\sigma \leftrightarrow z'h(x,y).$$

The boundary conditions used with the equations are the following: the bottom and shore are taken as no-slip, impermeable, no-flux surfaces; inflows or outflows along with appropriate fluxes of heat and salinity are specified at rivers: at the water surface, a wind-dependent stress, a specified heat flux, and a zero flux for salinity are specified. The initial conditions used are either some simple specification for the variables (e.g., zero) or specification of all variables from some previous calculation.

The equations are put into finite-difference form in both space and time. The spatial discretizing is accomplished by integration of the differential equations about appropriate grid cells. The equations are explicit in time, except with respect to the Coriolis terms and the vertical diffusion terms which are written implicitly. This is done to eliminate the small vertical diffusion time step restriction and the instability associated with explicit form of the Coriolis terms.

The equations as written can not be solved directly if the rigid-lid condition is to be satisfied. To develop a solution scheme, an additional equation is derived directly from the other equations and the rigid-lid condition. This equation is derived by vertically summing the two difference equations for the horizontal velocities, then taking the difference analog of the divergence. The rigid-lid condition is used along with the vertically summed continuity and hydrostatic pressure equations. The result is a Poisson-type difference equation in the surface pressure. The surface pressure is the "integration constant" resulting from the vertical summation of the hydrostatic pressure equation. The surface pressure is a function of the horizontal coordinates. This procedure for deriving the Poisson-type equation for the surface pressure, a modification of the SMAC procedure by Amsden and Harlow (1970), is different than previous models which first derived the pressure equation from the differential equation, then discretized it (Paul and Lick 1974, Paul 1976). The distinction between these two procedures is that with the use of the latter, the finite-difference equation that results for the pressure will not necessarily be directly deriveable from the finite-difference forms of the horizontal momentum equations. This is strictly a numerical error associated with approximating the differential equations; however, this error reflects in the inability of the numerical solution to satisfy the rigid-lid condition to an acceptable degree. Even if direct methods are used to solve the finite-difference pressure equation or if an iterative procedure is used

with stringent convergence criteria, errors are manifested in the vertical velocity at the rigid lid. These errors are not always small, especially in problems where there is significant differences in depths between the shallow and deep areas of the water body. These errors might not appear to be of much significance in some calculations, but they do create appreciable errors when the resultant velocities are used to calculate dispersion of substances in the body of water. Also, if advantage is taken of the time implicit nature of the vertical diffusion terms (i.e., time steps are large with respect to the explicit vertical diffusion time limit), these errors become large and ultimately make the solutions meaningless. Complete details of this numerical procedure appear in the report by Paul and Lick (1978).

Summary of Dispersion Component

The transport and dispersion of material in the turbulent flow will be described in a manner similar to that used for the transport and turbulent dispersion of heat and momentum. Refer to Sheng (1975) for a summary of this procedure. The concentrations of the material to be dispersed are treated as continuous on the length scales considered. The concentrations are sufficiently small so that they do not significantly alter the density of the water (the momentum equations can be solved independently), and they function as completely conservative substances in the water column convected with the local fluid velocities. The only exception to the latter condition will be when gravitational settling is important for the material considered. In this situation, the vertical convection of the material is enhanced by a settling velocity. The basic equation used to predict the dispersion of the material is:

$$\frac{\partial C}{\partial t} + \frac{\partial (Cu)}{\partial x} + \frac{\partial (Cv)}{\partial y} + \frac{\partial (Cw)}{\partial z} = \frac{\partial}{\partial x}\left(D_H \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_H \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_V \frac{\partial C}{\partial z}\right), \quad (8)$$

where

C = concentration of material per unit volume,

x,y = horizontal coordinates,

z = vertical coordinate,

t = time,

u,v = particle (or fluid) velocities in the x and y directions,

w = particle velocity (the sum of the fluid velocity and the settling velocity, w_s, of the substance relative to the fluid) in the z direction,

D_H = horizontal eddy diffusivity, and

D_V = vertical eddy diffusivity.

The boundary conditions used are that all surfaces have zero net flux of the material through them except at rivers. In this latter situation, the net flux is either into or out of the water, depending on the flow of the river. The magnitude of the flux depends on the local concentration of the material. The same transformation of the vertical coordinate that is used for the hydrodynamic component is used here. The finite-difference analysis of the equation is similar to that used for the hydrodynamic component. Paul and Patterson (1977) have used this basic dispersion component to calculate the transport of larval fishes in the western basin of Lake Erie.

TRANSPORT MODELS

Type 1 Transport Model

In this section, a model of water exchange between different regions of a water body will be presented. It is important because water exchange determines, to a considerable degree, the changes in the concentration of solutes, phytoplankton, zooplankton, etc., in the water mass. These changes are very substantial for the ecosystem as a whole.

A universal means of solving such problems involves the use of hydrodynamic equations for calculating the currents in a body of water, and the subsequent calculation of the dynamics of concentrations of the material, by means of a turbulent diffusion equation, on the basis of the flow pattern obtained. This turbulent diffusion equation is:

$$\frac{\partial C}{\partial t} = - \text{div } (C \cdot u) + \text{div } (E, \text{grad } C) + y \qquad (9)$$

where

C = concentration of the material,

t = time,

u = velocity vector,

E = turbulent diffusivity, and

y = source or sink term.

In practical calculations, the differential relations are replaced by their finite-difference analogs. The computations (usually done with a computer) are performed for discrete instants of time on a discrete grid which approximates the body of water.

Let us now consider a description of the calculations for the concentration dynamics of the material. Let the body of water be divided into n regions, each of which is assumed to be homogeneous in concentration. The following notation is introduced:

C_i^t - concentrations of material at time t in region i,

V_i^t - volume of region i at time t,

y_i^t - external loading of material into region i between times t and t+1,

Q_{ij}^t - volume of flow from region i to region j at time t, and

K_i - first order decay coefficient of the material.

The equation for the concentration dynamics of the substance is:

$$C_i^{t+1} = [C_i^t(V_i^t - \Sigma_j Q_{ij}^t) + \Sigma_j Q_{ij}^t C_j^t + y_i^t - K_i V_i^t C_i^t]/V_i^{t+1}, \quad i=1,2,\ldots,n \qquad (10)$$

The terms on the right hand side of Equation (10) have the following meanings:

$C_i^t V_i^t$ - amount of material in region i at time t,

$C_i^t \Sigma_j Q_{ij}^t$ - amount of material transported out of region i to all neighboring regions,

$\Sigma_j Q_{ij}^t x_j^t$ - amount of material transported into region i from all neighboring regions,

y_i^t - external loading into region i,

$K_i V_i^t C_i^t$ - chemical decomposition in region i.

In conformity with the two terms on the right hand side of the turbulent diffusion equation (9), the quantities Q_{ij} are assumed to consist of two terms:

$$Q_{ij} = Q_{ij}^{I} + Q_{ij}^{II}.$$

The first term corresponds to the transport between regions i and j due to the mean currents, and the second term describes the mixing due to fluctuating disturbances relative to the mean currents.

The equation of concentration dynamics (10) makes it possible to compute the concentrations x^{t+1} only if values for all the variables on the right hand side of the equation are known. The values of concentration x^t for the previous time step are assumed to have been computed or specified as initial conditions. The values y^t of loadings of the material have to be specified. The decay constants, K_i, of the material may be different for separate regions of the body of water because of possible differences in physicochemical conditions of the region, and must also be specified. The

remaining values of the volumes, V_i^t, V_i^{t+1}, of each of the regions and flows, Q_{ij}^t, depend on the hydrological regime. They may be either specified or computed separately.

Thus, equation (10) can be used for different purposes. If the conditions in the body of water are sufficiently stable, one can calculate the steady state of the concentrations by equating quantities at times t and t+1. This results in:

$$C_i = C_i \left(1 - \frac{1}{V_i} \sum_j Q_{ij}\right) + \frac{1}{V_i} \sum_j Q_{ji} C_j + y_i - K_i C_i,$$

$$i = 1,2,\ldots,n \qquad (11)$$

Simple rearrangement results in the equation

$$AC = y,$$

where A is a square matrix of order n with coefficients

$$A_{ij} = \begin{cases} K_i + \frac{1}{V_i} \sum_j Q_{ij}, & \text{for} \quad i = j \\ -\frac{1}{V_i} Q_{ji}, & \text{for} \quad i \neq j \end{cases}$$

and C and y are column vectors with components C_i and y_i, respectively.

The steady state results are obtained as the solution of the linear system

$$C = A^{-1} y.$$

Hence, if the values of flow, Q_{ij}, between the regions are specified or estimated in some manner, and if the concentrations of the material may be considered to be in a steady state, then from a given loading y, one can compute the concentration distribution.

The second method of using Equation (11) consists of computing the transient concentrations C. The transient values of volumes, V_i^t, and flows between regions, Q_{ij}, can be computed with a suitable hydrological model. For a shallow body of water characterized by wind-driven flow, this can be done by means of a model analogous to the one used for simulating the hydrologic regime of the Sea of Azov.

In this model, a time step of 5 days was chosen. It was assumed that for a 5-day average wind velocity vector there exists a corresponding slope of the water surface, which to a first approximation was assumed to be an ideal plane. These assumptions were based on data from natural observations and level fluctuations of the Sea of Azov.

The sequence of the calculations in the model is as follows: first, the average surface elevations of each of the regions are calculated from the average wind velocity vector. From the surface elevation of the region, the volume V_i^{t+1} is calculated. Comparison of V_i^t and V_i^{t+1} indicates that an increase (or decrease) of water is required by region i. From the arrangement of the regions, one determines from which adjacent region this water is transported. Also considered are inflows of water with river runoffs, and the balance of evaporation and precipation at the sea surface.

Type 2 Transport Model

An economical approach to quantifying circulation in segmented water bodies has been developed by Thomann (1972). This approach utilizes one of the basic conservation principles, mass balance, to trace a material through segmented systems. Any material for which the reactions are known may be used as the tracer. For Lake Ontario and Lake Huron, Thomann, et al., (1975), and DiToro and Matystik (1976) have used temperature as a transport tracer. For Saginaw Bay, chloride is an appropriate tracer because of the large source in the Saginaw River and the relatively sharp gradients in the bay.

Richardson (1974 and 1976) has calibrated and verified a quasi-steady-state chloride transport model for Saginaw Bay. The approach used is depicted in Figure 8. Given a chloride river loading and chloride concentrations in the bay, the circulation parameters become the unknowns. These parameters are determined through an iterative process using a computer solution of the mass balance formulations given below:

$$V_k \frac{dc_k}{dt} = 0 = \sum_j [-Q_{kj} (\alpha_{kj} c_k + \beta_{kj} c_j) + E'_{kj} (c_j - c_k)] - V_k K_k c_k + W_k,$$

where

c_k = concentration per unit volume (M/L^3),

K_k = decay coefficient ($1/T$),

E_{kj} = dispersion coefficient (L^2/T),

V_k = volume of segment k (L^3),

E'_{kj} = bulk dispersion coefficient = $E_{kj}A_{kj}/\bar{L}_j$ (L^3/T),

$\bar{L}_j$ = average length of adjacent sections (L),

A_{kj} = cross-sectional area between segments k and j (L^2),

α_{kj} = dimensionless coefficient to account for unequal segment dimensions,

β_{kj} = $1 - \alpha_{kj}$,

Q_{kj} = advcective transport parameter (L^3/T), and

W_k = source of c in mass units per time (M/T).

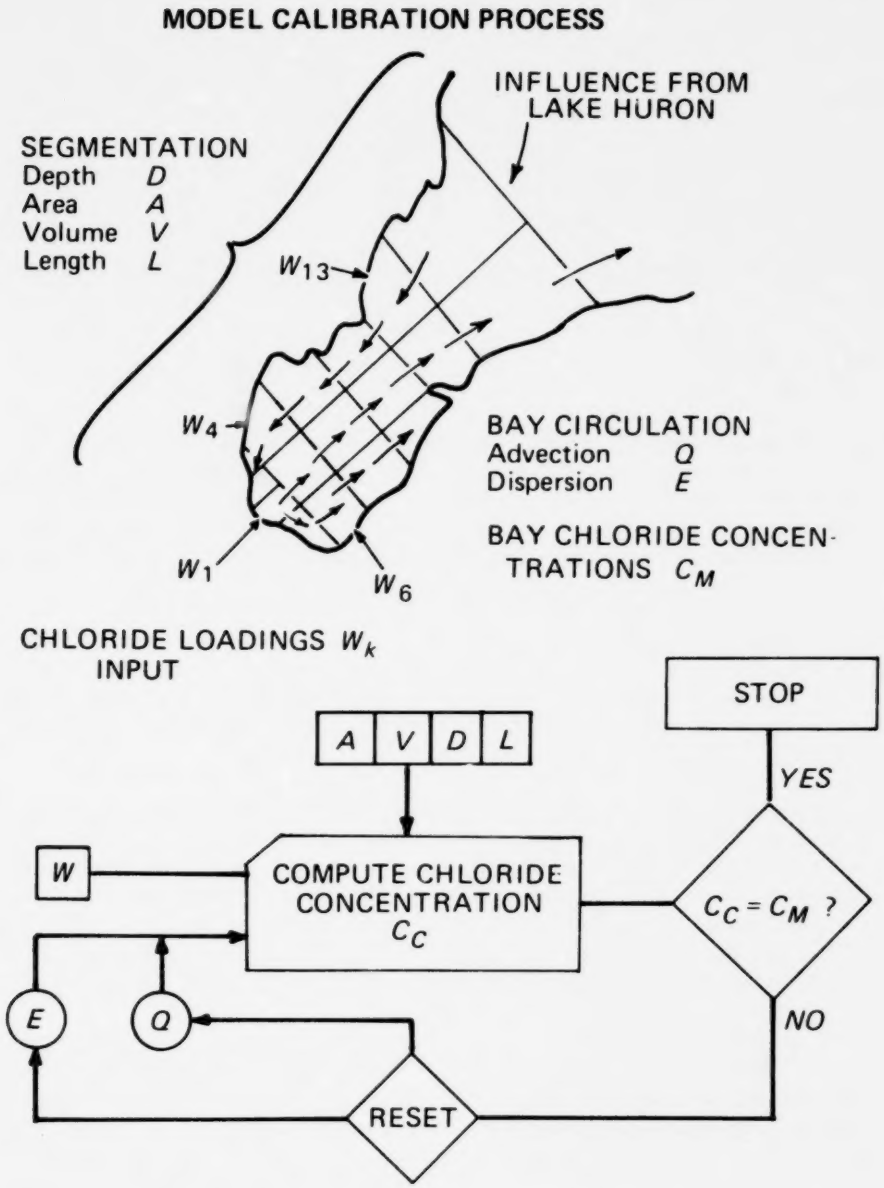


Figure 8. Type 2 transport model calibration process for Saginaw Bay.

The units are:

L = length,
T = time, and
M = mass.

The parameters α_{kj} and β_{kj} are determined by:

$$\alpha_{kj} = \frac{\bar{L}_j}{\bar{L}_j + \bar{L}_k},$$

where positive solutions to the equations are guaranteed by the criterion

$$\alpha_{kj} > 1 - \frac{E'_{kj}}{Q_{kj}} .$$

Initial estimates of the transport parameters for dispersion, E, and advection, Q, are made, and concentration of chloride is computed. The computed concentrations are compared to the measured average concentrations in each segment. The process of selecting new values of E and Q, directed by the magnitude and direction of the previous error, is repeated until the computed concentrations are approximately equal to that measured.

Comparison of Transport Models

The two transport models are similar in that they try to predict water movements with basic conservation equations. They differ by which conservation equation is used.

The type 1 model (Gorstko and Surkov) calculates the changes in water movement with time by using surface elevation changes. For the application to the Sea of Azov, the water surface slope is related to a time-averaged wind. By neglecting diffusion, a unique set of water transports from one time step to the next is calculated. A difficulty with this model is that a non-zero steady-state solution for water transport cannot be calculated because it only calculates transports resulting from the changes in surface elevation.

The type 2 model (Richardson) calculates water movement and diffusive transport through an iterative process of comparing computed and observed material concentration values. A set of time-dependent transports is developed with this model that gives reasonable agreement with observed data, i.e., the transports are adjusted until the agreement is satisfactory. Since water movement and diffusion are both solved for, a unique solution is not obtainable because the equations are underdetermined. This model does require a reasonable data base of observed concentrations if the time-dependent transports are to be characterized with some degree of resolution. The iterative procedure has not been automated so it does require extensive user interaction.

The choice of transport model which is better for a particular application depends on the data available and the physical characteristics of the water body.

SECTION 7

RESULTS

LAKE BAIKAL

Hydrodynamic and Dispersion Calculations

The parameters used for the application of the hydrodynamic model to Lake Baikal are listed in Table 6. The vertical diffusion is dependent on the local depth, resulting in larger mixing in the deeper sections of the lake. Figure 9 indicates the horizontal grid scheme used for the discretization process. Constant-density calculations were performed for the four main wind directions on the lake; these are listed as Cases 1 through 4 in Table 6. These main wind directions are the same as indicated in the Baikal Atlas (Anonymous 1969). Figure 10, taken from the Baikal Atlas, indicates the relative frequency of the four wind directions during the summer and autumn periods. The water current data with which the calculations are compared is only of a general nature since lakewide currents for specific episodes in time were not obtainable during the course of this study. Since an insufficient amount of data was available on the thermal regime for the entire lake, the calculations were performed assuming this aspect to be negligible. The wind direction for Case 1, from the southwest, was also used in a calculation with the northern basin of the lake ice covered. This type of calculation is of interest to assess the significance of the ice cover on the central and southern basins. The northern basin is generally ice covered through the middle of May, and occasionally until the beginning of June (Anonymous 1969).

Detailed results of the hydrodynamic calculations are presented in Appendix C. All of the calculations were performed for 12 days of real time, after which essentially steady-state conditions were obtained. Figures 11 and 12 show the surface velocities and vertically integrated velocities for the southwest wind (Case 1) and the northwest wind (Case 3). For all of the calculations, the results are typical of what might be expected from the simple theory of motion which balances Coriolis force, vertical friction, and horizontal pressure gradients. The deep areas of the lake are generally characterized by geostrophic motion, while the shallower areas are markedly influenced by vertical friction. The magnitude and directions of the surface currents indicate the different balances in the motion as one goes from shallow to deep waters. The general circulation of the lake is composed of the basic circulation in the three basins. Because the northern and southern basins are relatively flat in their long dimension compared with the central basin, the magnitude of the vertically integrated velocities for the southwest wind are smaller in these basins

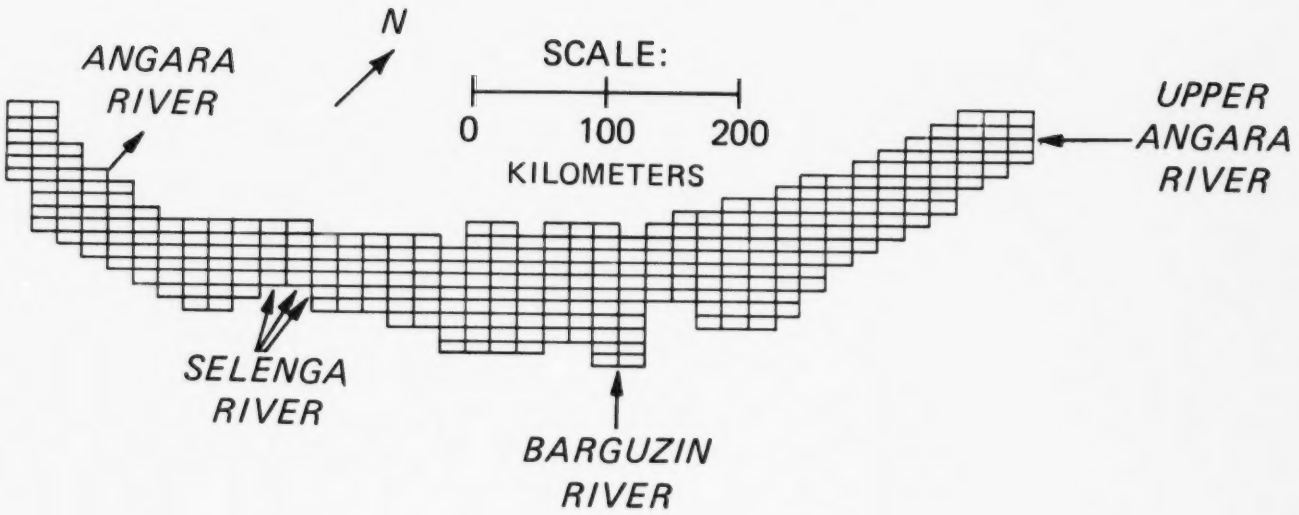


Figure 9. Hydrodynamic model grid for Lake Baikal calculation.

TABLE 6. PARAMETERS FOR LAKE BAIKAL HYDRODYNAMIC MODEL

Grid spacings	15 km y-direction 7.8 km x-direction
Horizontal extents	600 km y-direction 150 km x-direction
Number of grid points	41 y-direction 21 x-direction 8 z-direction
Minimum depth	10 m
Maximum depth	1620 m
Coriolis parameter (53°N)	1.16×10^{-4}/sec
Horizontal eddy viscosity	10^7 cm^2/sec
Vertical eddy viscosity	$3.85 \left(1 + 258.7 \frac{h}{h_o}\right)$ cm^2/sec
Surface wind stress	1 dyne/cm^2
Wind directions:	
Case 1	Southwest
Case 2	Northeast
Case 3	Northwest
Case 4	Southeast
River flows:	
Selenga	9.64×10^8 cm^3/sec
Barguzin	4.10×10^8 cm^3/sec
Upper Angara	5.78×10^8 cm^3/sec
Angara	19.52×10^3 cm^3/sec
Horizontal eddy diffusivity	10^6 cm^2/sec
Vertical eddy diffusivity	$.385 \left(1 + 258.7 \frac{h}{h_o}\right)$ cm^3/sec
Particle settling velocity	10 m/day

where:

h = local depth
h_o = reference depth

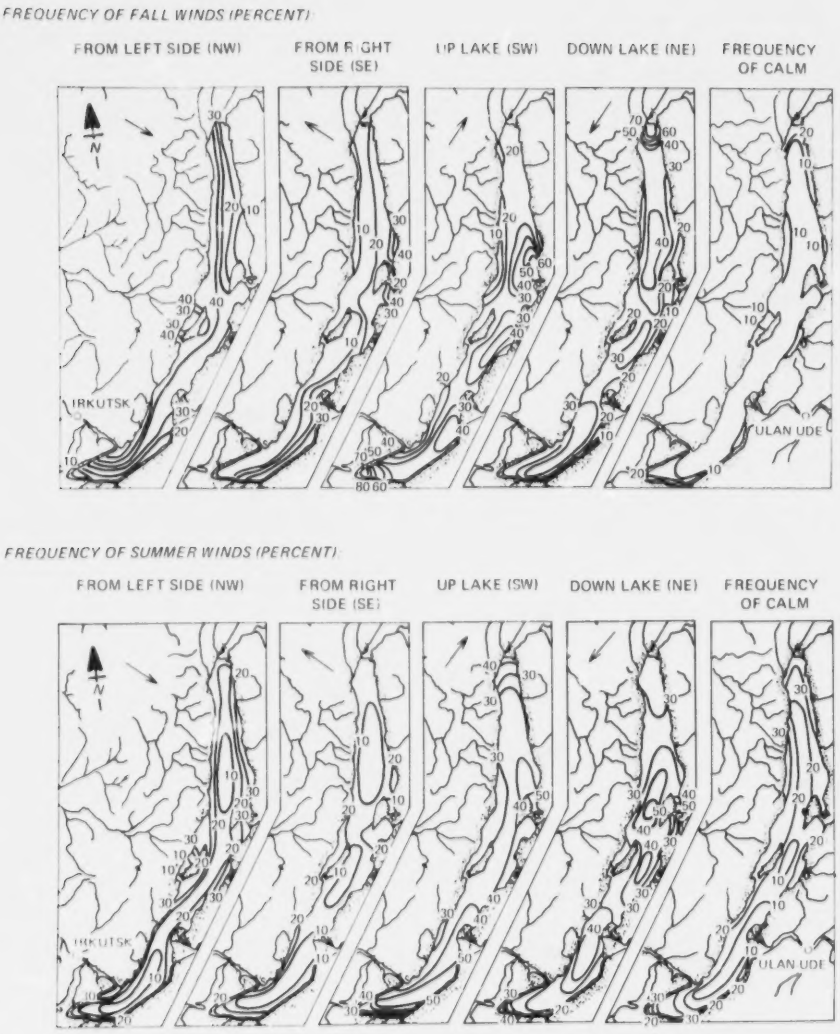


Figure 10. Frequency of winds over Lake Baikal in the summer and autumn.

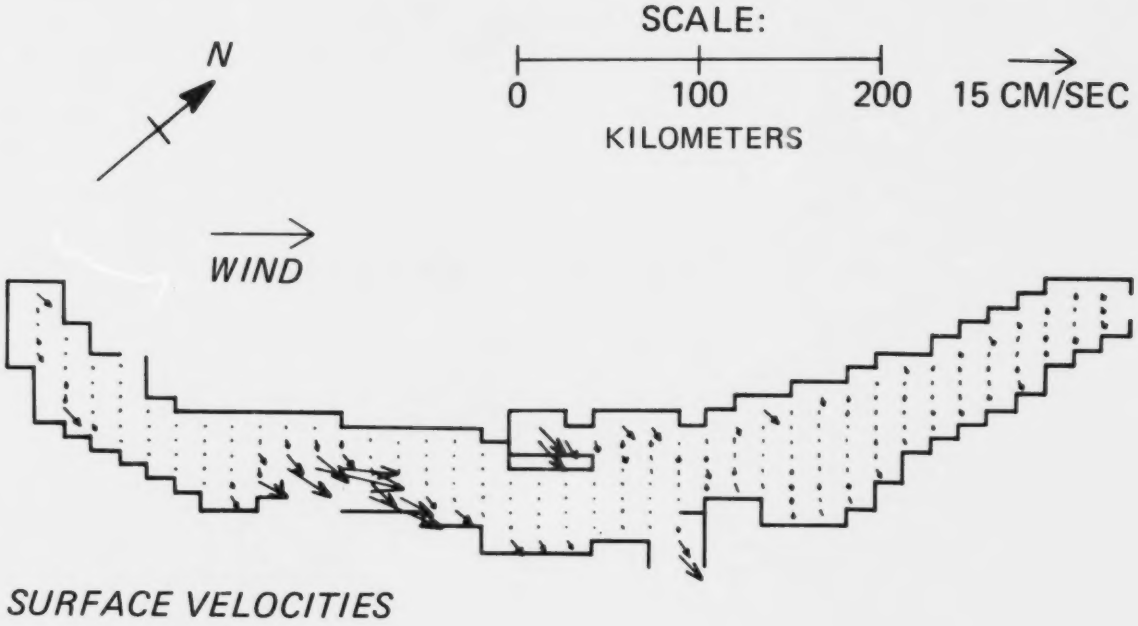


Figure 11a. Hydrodynamic model calculation for Lake Baikal with southwest wind.

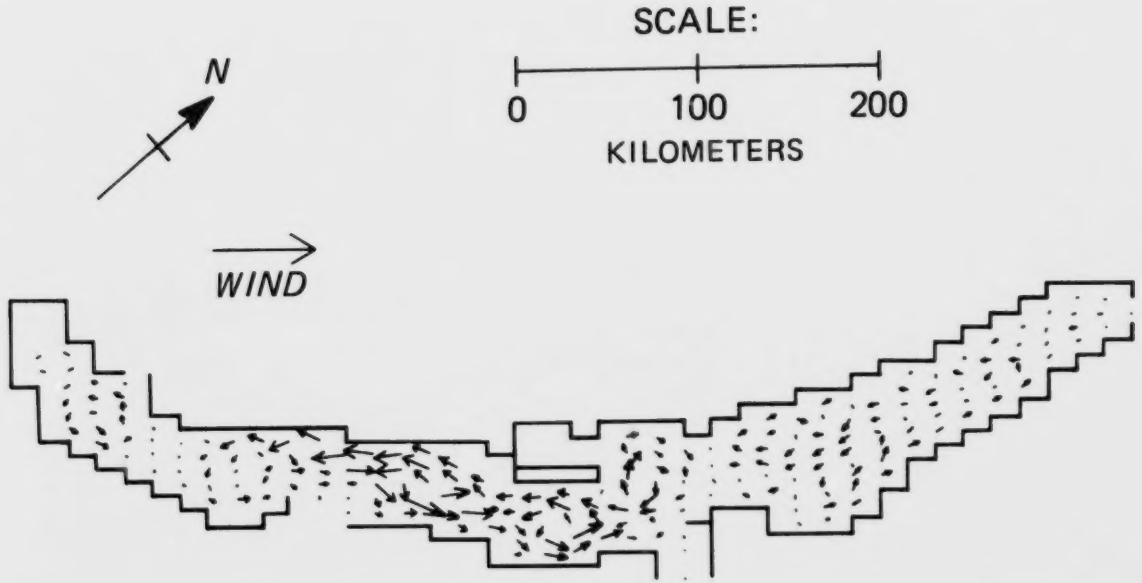


Figure 11b. Hydrodynamic model calculation for Lake Baikal with southwest wind.

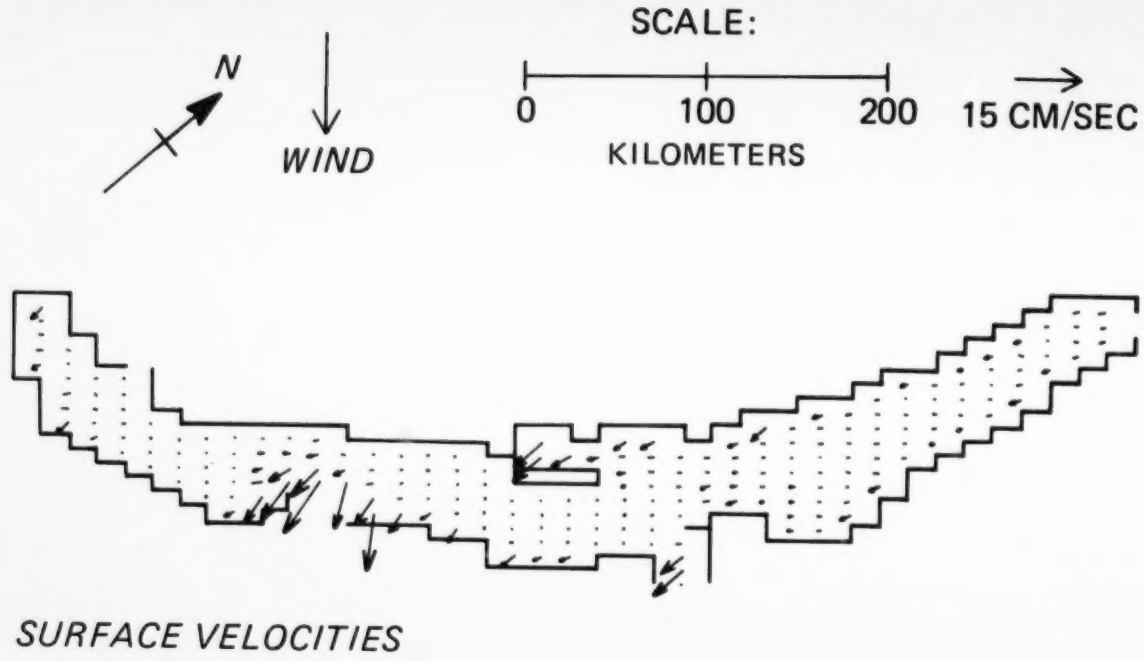


Figure 12a. Hydrodynamic model calculation for Lake Baikal with northwest wind.

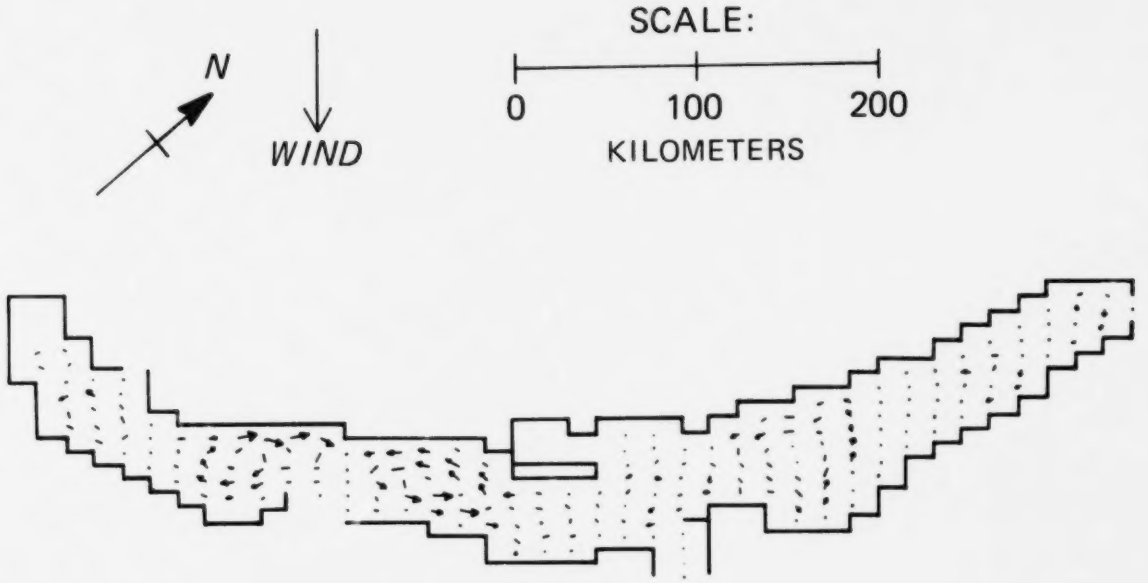


Figure 12b. Hydrodynamic model calculation for Lake Baikal with northwest wind.

compared to the central basin. This is in agreement with the steady-state solutions obtained for simple basins by Gedney (1971). He solved the equations which balance Coriolis force, pressure gradients, and vertical friction. For constant depth basins, the steady-state vertically integrated velocities are everywhere equal to zero, while for parabolic shaped basins, the vertically integrated velocities form two rotating gyres, with the magnitudes dependent on the degree of the bottom slopes. Thus, the gyres in the calculations for the vertically integrated velocities are functions of the local topography. Differences are apparent for the different wind direction calculations, but this is because the basins are elongated and the topography is highly variable.

The surface velocities and vertically integrated velocities for a southwest wind with the northern basin covered with ice are shown in Figure 13. It can be seen that the currents in the central and southern basins are relatively unaffected by the ice cover. The currents in the northern basin are almost non-existent, because the lake currents are mainly wind-driven. The minimal current that does exist in this basin is primarily due to the inflow of the Upper Angara River.

Data on surface currents in the Selenga region were presented earlier in Figure 3. Three cases were shown: prevailing southwesterly winds, prevailing northwesterly winds, and steady lasting northwesterly winds. The first two are separated by only a day, and it is apparent that the currents on the second day show the effects of the previous day's winds. This can be seen by comparing the second and third plot. The currents in the third plot compare quite well with the surface current calculation for the northwesterly wind (Figure 12). The first plot compares reasonable well with the calculation for the southwesterly wind (Figure 11), but discrepancies do exist, apparently a function of the transitory behavior of the currents. The second plot appears to be some combination of the two calculations, as would be expected.

The only data for lake-wide currents is a plot which appears in the Baikal Atlas (Figure 14). This is depicted as representative of the typical currents that exist in the lake. With reference to the wind frequency plot for the lake (Figure 10), it can be seen that for the most part, the winds from the southwest are the most typical. A comparison of the data plot (Figure 14) with the vertically integrated velocities calculated for a southwest wind (Figure 11) indicates a very good agreement. The observed gyres are replicated quite well in the calculation. The data plot does not indicate magnitudes of the currents so no comparisons can be made on this aspect.

Using the steady-state currents that were calculated, the transport and dispersion of material in the lake were calculated. A series of 8 calculations were performed: for each of the four main wind directions, for material which is neutrally buoyant and for material which has a gravitational settling velocity of 10 meters per day. This settling velocity corresponds with the mean Stokes settling velocity for the predominant particle sizes observed in the suspended material in the Selenga River runoff (see Appendix B). The two calculations for each current pattern in-

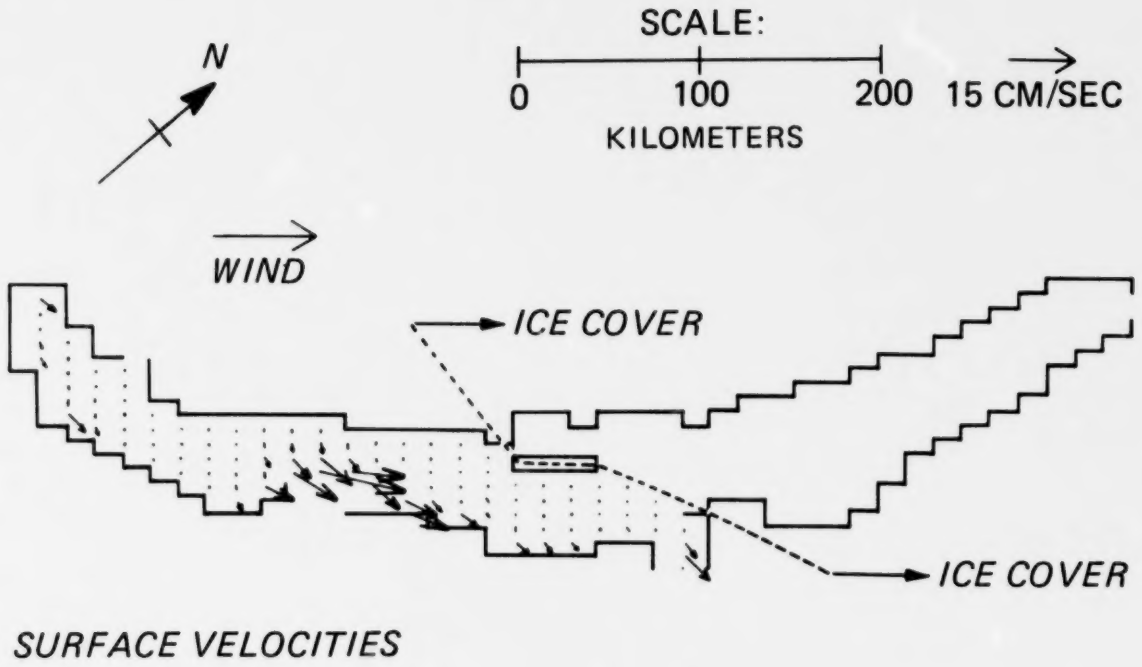


Figure 13a. Hydrodynamic model calculation for Lake Baikal with southwest wind and northern basin ice covered.

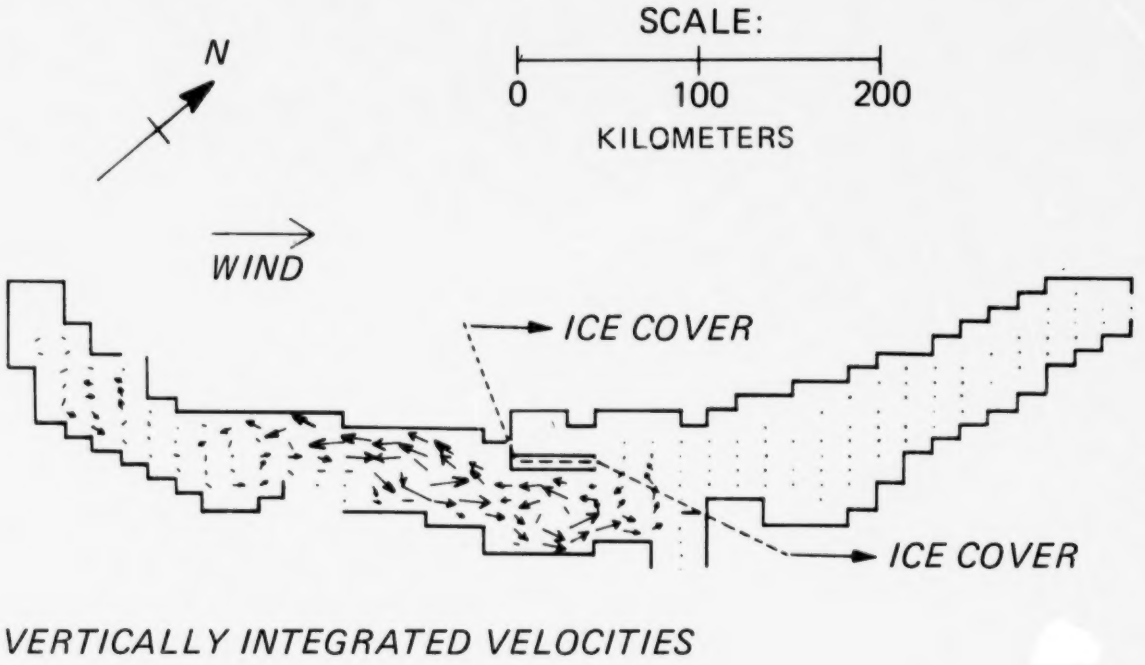


Figure 13b. Hydrodynamic model calculation for Lake Baikal with southwest wind and northern basin ice covered.

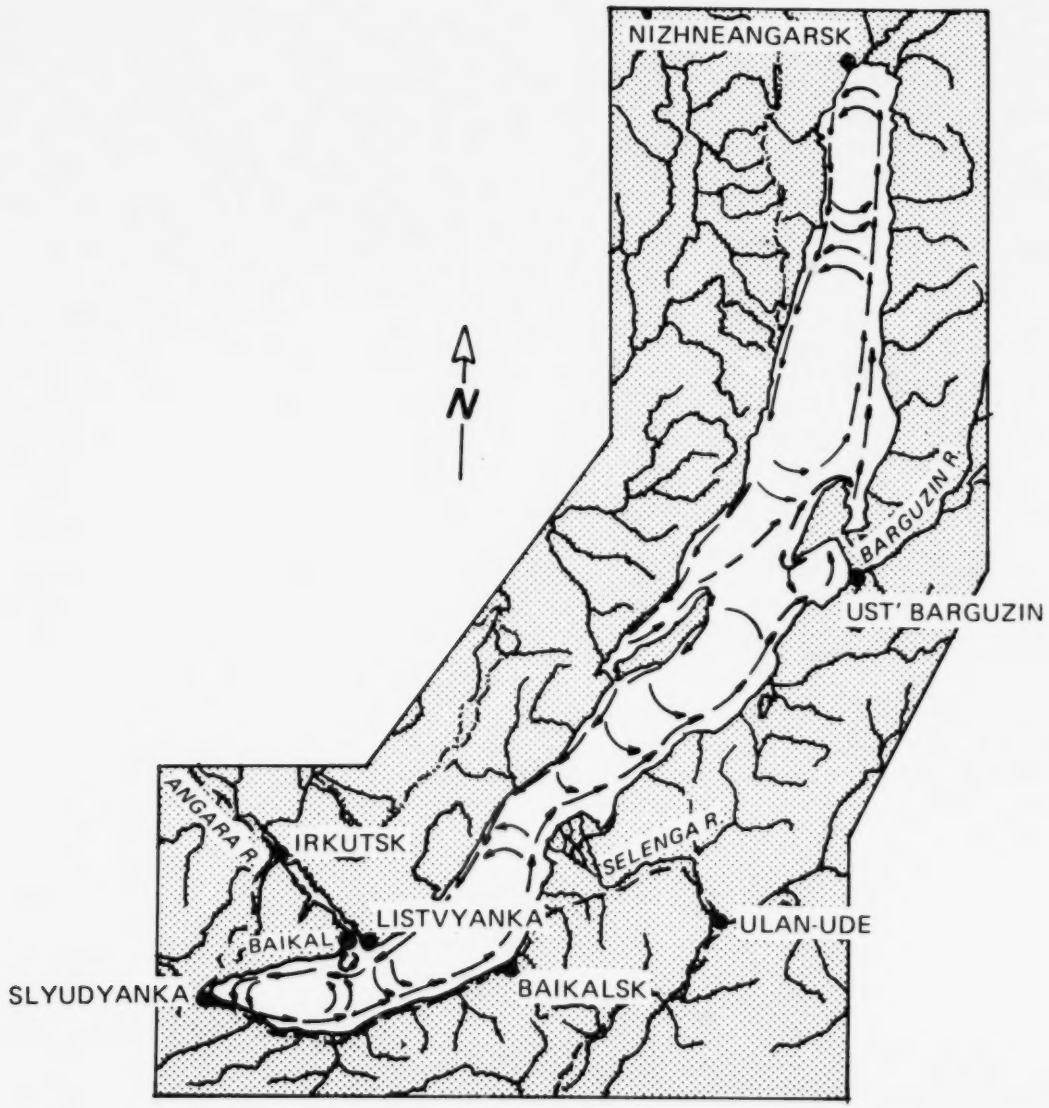


Figure 14. Lake Baikal whole lake dominant currents.

dicate the difference in distributions that can be achieved when one considers dissolved material (neutrally buoyant) and suspended material (positive settling velocity). The parameters used for the calculations are listed in Table 6. The calculations were performed for 28 days of real time for each circumstance. Material was entered continuously during the calculation through the Selenga, Barguzin and Upper Angara Rivers. The material concentration in each river was set equal to 1.0. Since the transport equations are linear in the material concentration, the actual concentration level is not important in the calculation. The results for all the calculations are presented in Appendix C. Figure 15 indicates surface and bottom concentrations with a southwest wind for both neutrally buoyant and suspended material. The effect of the settling velocity on the concentration distributions is important. The main reason for this is that the currents over the water column are, in general, going in different directions. If the material remains essentially uniform over the water column (i.e., for the neutrally buoyant material), then the material is primarily transported by the currents over the upper portion of the water column. These are the currents which have the larger magnitude. When gravitational settling is introduced, the material tends to concentrate near the bottom, and thus, is transported horizontally by the currents that are near the bottom. Since these currents are in generally in a different direction than the near surface currents, the concentration distribution appears different.

The data that is available for comparison with the calculations are shown in Figure 16. These data are taken from the Hydromet cruise in the Selenga River Region of the lake on May 28-29, 1976 (refer to Appendix D for the data that was available for this study). The plots are for PO_4^{-3} (a dissolved substance) and total suspended solids. The winds over the region were highly variable during the cruise, ranging from southwest to southeast during the first part of the cruise, and to northeast during the final part of the cruise. A reasonable comparison can be made with the calculations for the southwest wind (Figure 15). The currents in the vicinity of the Selenga delta are easterly near the surface and over most of the vertical column near the river area of the lake. As one goes away from the river area, the subsurface currents are generally southwesterly. The suspended solids settle out as they enter the lake and are transported by the near-bottom currents. The dissolved material remains nearly uniform vertically, and is transported out into the lake by the subsurface currents. The data generally agree with the calculated distributions.

Additional data available for the Selenga region are the Landsat satellite images shown in Figure 17. These images record observations of June 21, 1975, and July 9, 1975. Unfortunately, no wind information was available for these dates. The images do indicate the same sort of suspended solids pattern as was observed during the May 28-29, 1976, Hydromet cruise (Figure 16).

Type 1 Transport Calculation

The steady-state transport model developed by Gorstko and Surkov (type 1) was applied to a 14 segment model of Lake Baikal. The segmentation

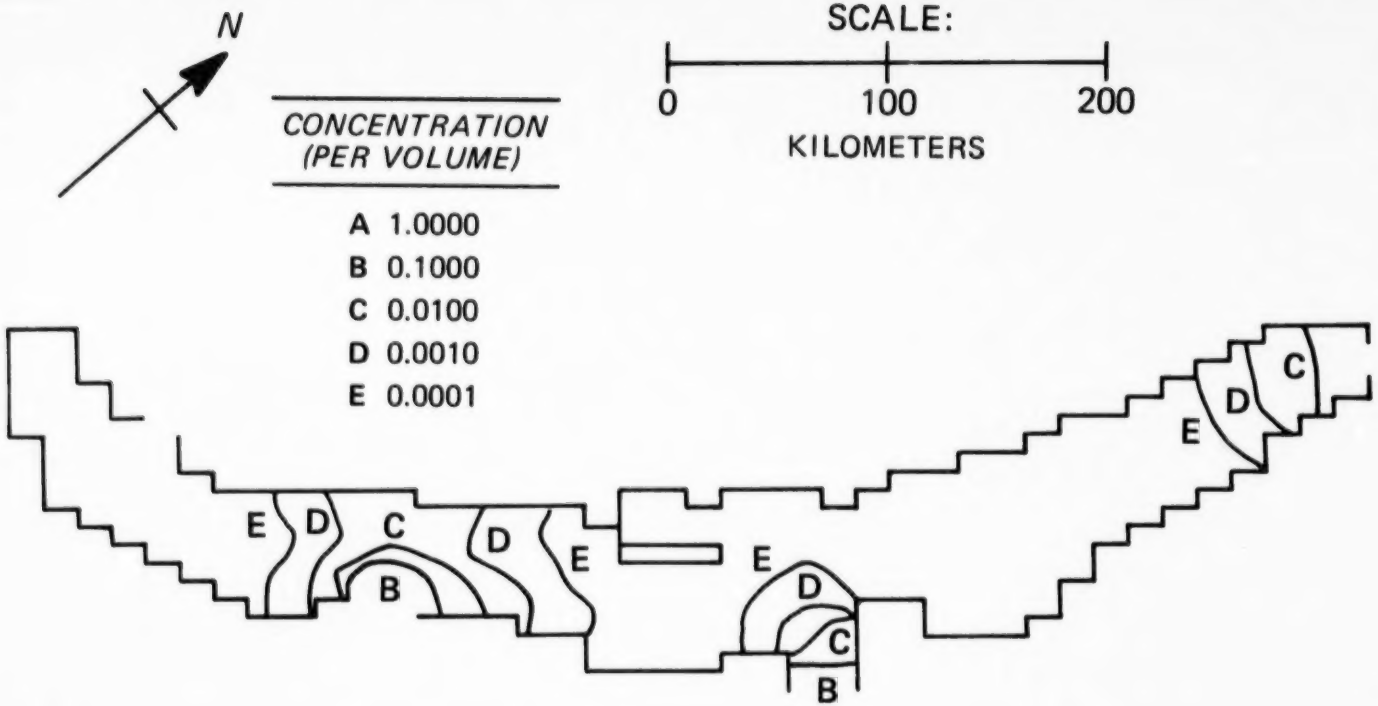


Figure 15a. Dispersion model calculation for Lake Baikal with southwest wind.

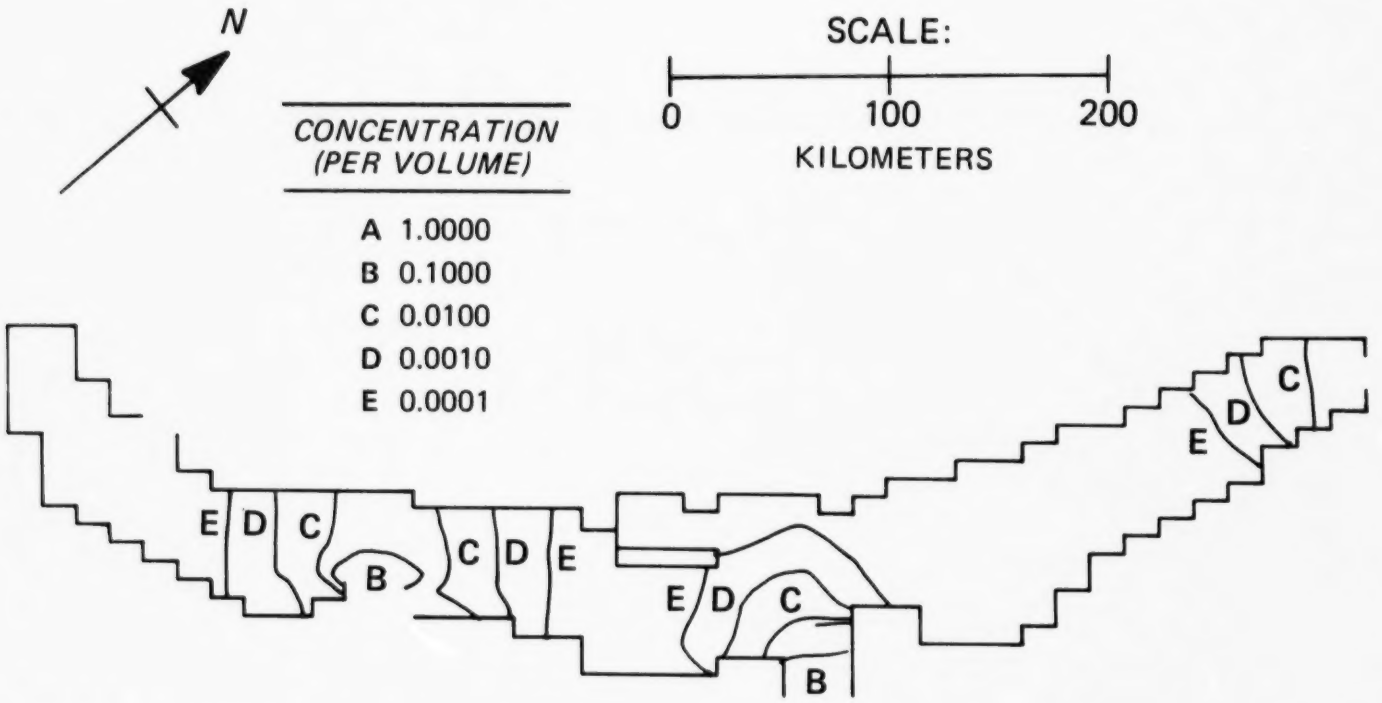


Figure 15b. Dispersion model calculation for Lake Baikal with southwest wind.

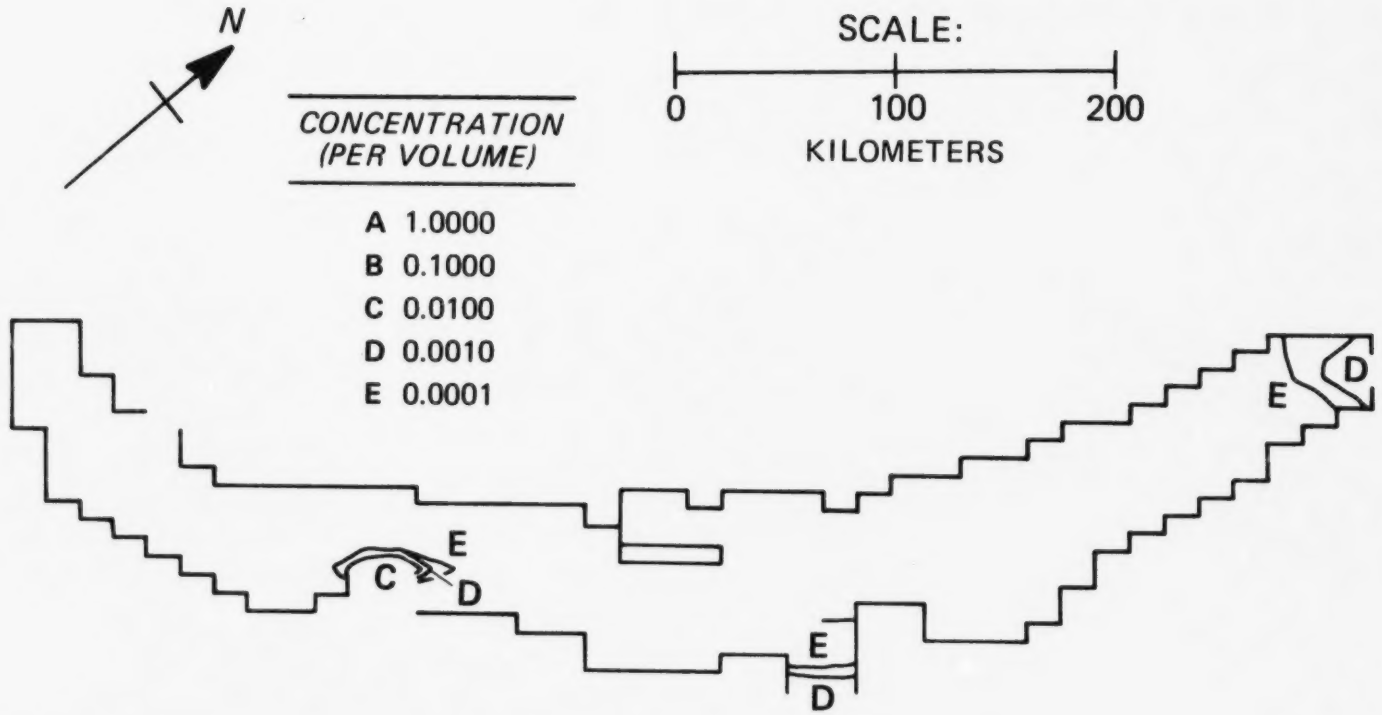


Figure 15c. Dispersion model calculation for Lake Baikal with southwest wind.

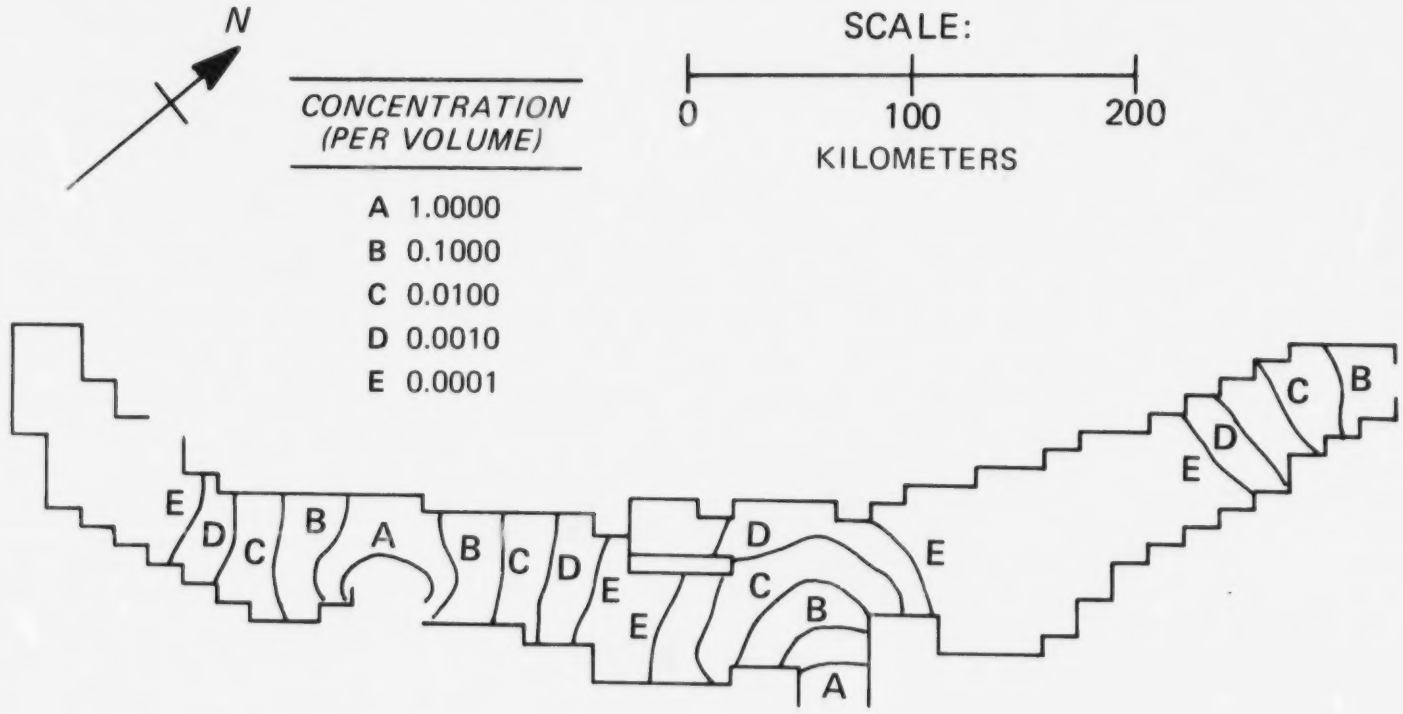


Figure 15d. Dispersion model calculation for Lake Baikal with southwest wind.

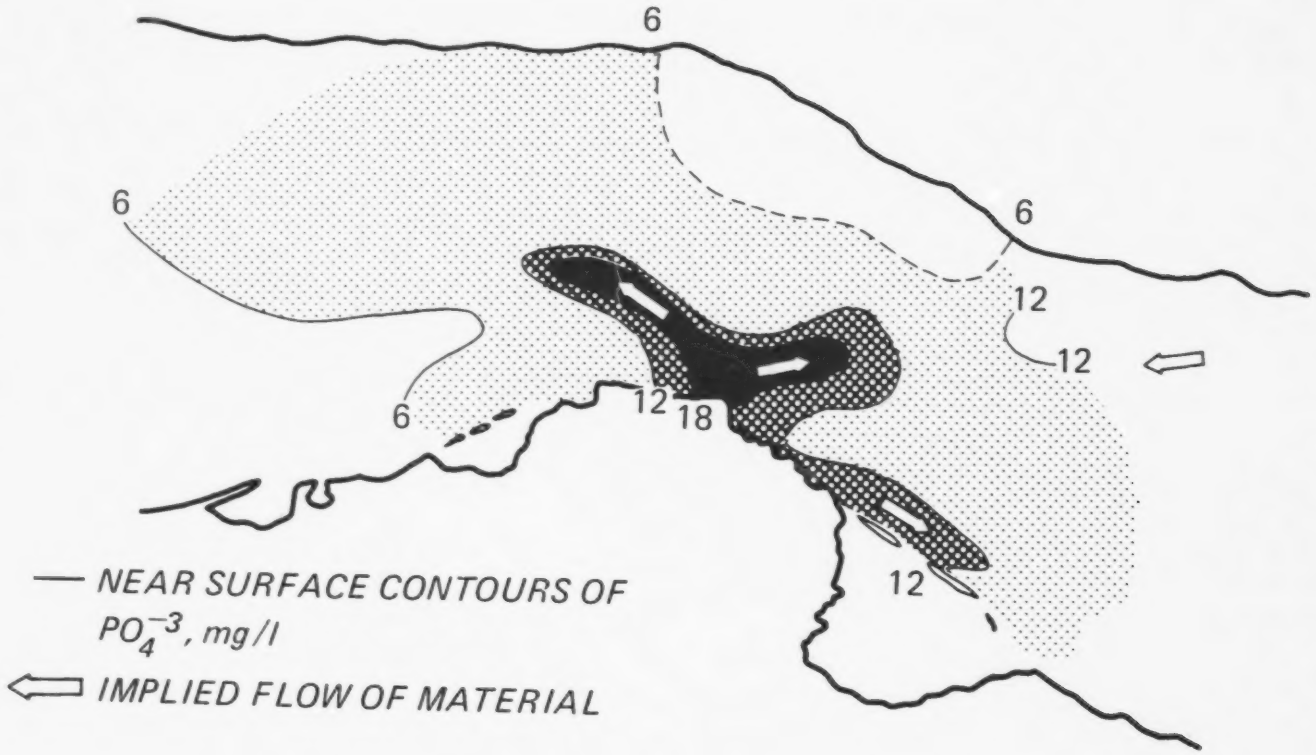


Figure 16a. Sample results from Hydromet cruise in Selenga Shallows on 28-29 May 1976.

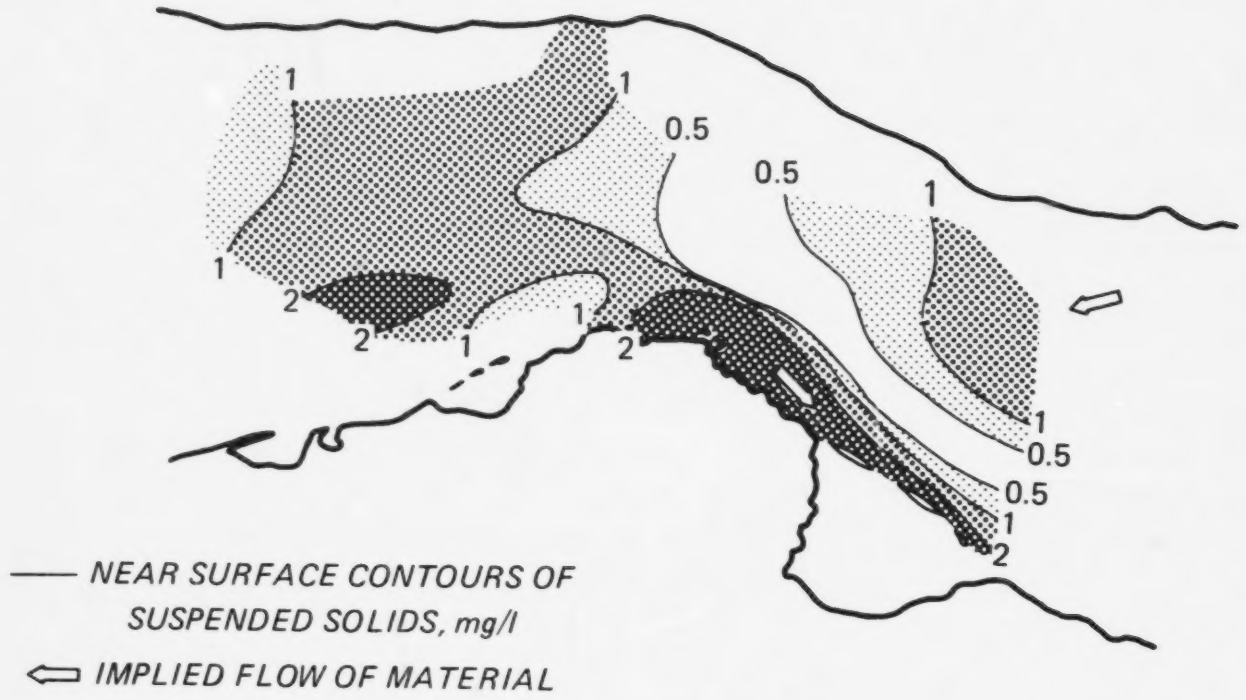


Figure 16b. Sample results from Hydromet cruise in Selenga Shallows on 28-29 May 1976.

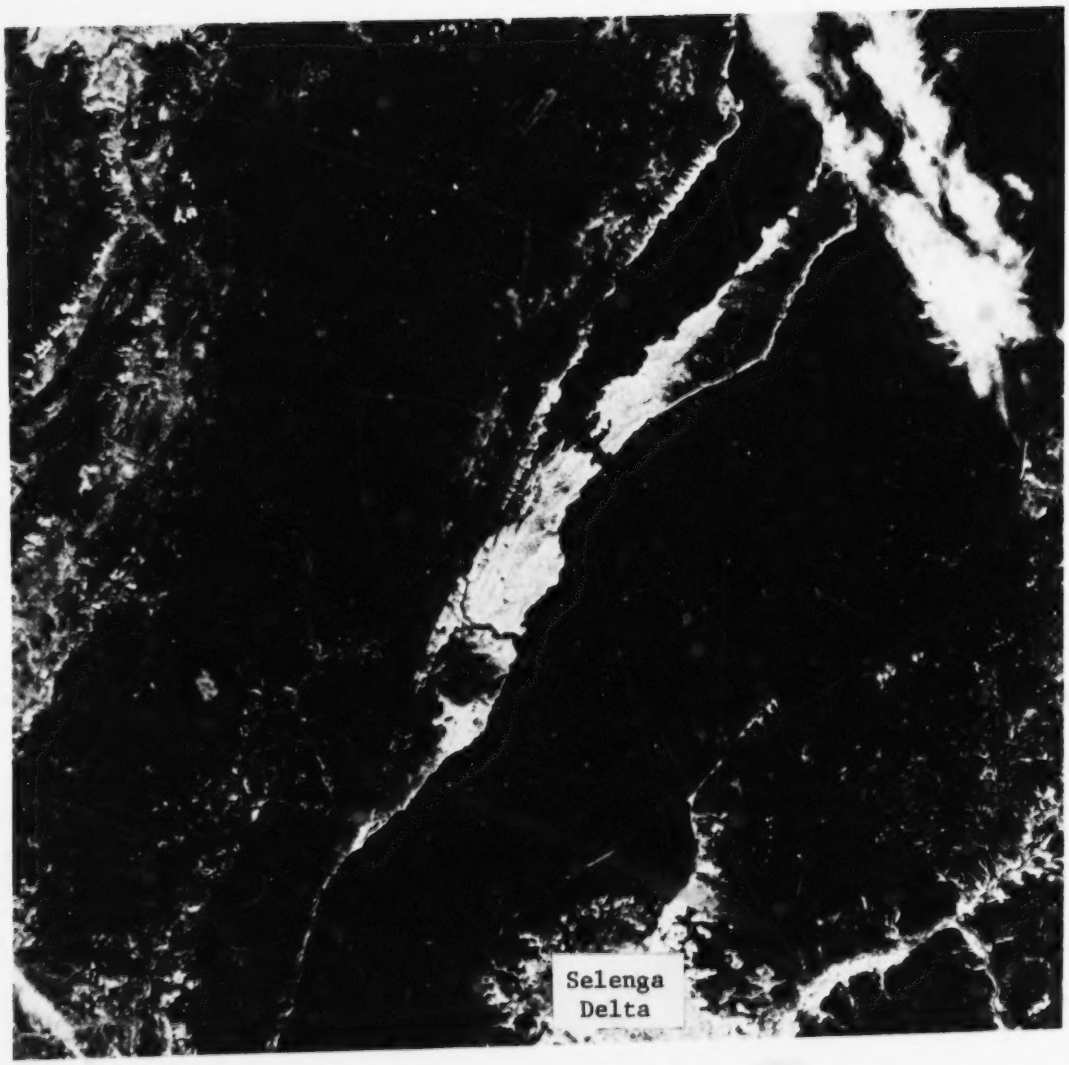


Figure 17a. Landsat satellite images of Lake Baikal.

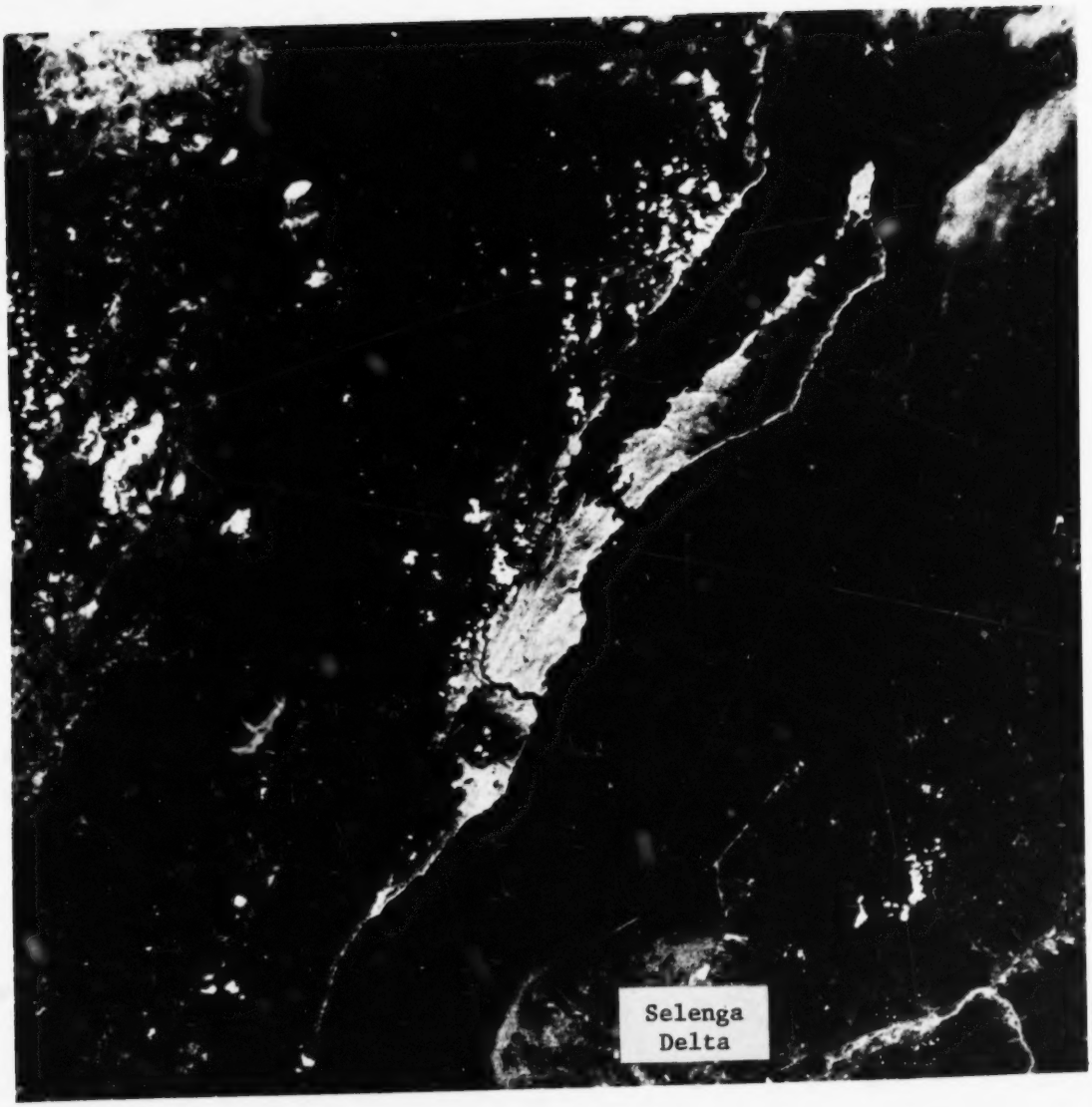


Figure 17b. Landsat satellite images of Lake Baikal.

scheme is indicated in Figure 18, and the segment characteristics are indicated in Table 7. The water exchanges between segments that were determined for typical winds over the lake are indicated in Figure 18. These water exchanges agree with the general lakewide circulation observed in the lake, shown in Figure 14 (Anonymous 1969).

SAGINAW BAY

Type 1 Transport Calculation

The type 1 steady-state model developed by Gorstko and Surkov (1975) was applied to a 16-segment model for Saginaw Bay. The segmentation scheme was identical to that used by Richardson (1976), and was applied to the 1965 data for chloride concentrations in the bay. The calculated and observed concentrations are shown in Figure 19 along with the water exchanges between segments that were determined. The calculated chloride concentrations agree with the observations, and the calculated water exchanges are similar to that determined by Richardson (1976), who applied the type 2 transport model under the same conditions. Refer to the next section for his analysis and results.

Type 2 Transport Calculation

Through an iterative process, a type 2 transport model for chloride in Saginaw Bay was calibrated and verified by Richardson (1976). Average chloride loads to the bay of 2.8 million kg/day and 1.2 million kg/day were measured in 1965 and 1974, respectively. The calibration with June-November 1965 data that was obtained is shown in Figure 20. Verification with June-November 1974 data is shown in Figure 21. Figure 22 shows the advective transport scheme used for both of these computations. Dispersion from segment to segment varies from about 3.9 km^2/day near the Saginaw River and along the southeast shore of the bay, to 14.6 km^2/day along the northwest shore.

SEA OF AZOV

Hydrodynamic and Dispersion Calculation

The parameters used for the application of the hydrodynamic model to the Sea of Azov are listed in Table 8. The equation-of-state is based upon the form used by Crowley (1968) for oceanic calculations. It is:

$$\rho - \rho_o = 10^{-3} (28.14 - .0735T - .00469T^2 + (.802 - .002T) (S-35)) \quad (11)$$

where

ρ = density of water (gm/cm^3),

ρ_o = 1 gm/cm,

Figure 18. Fourteen-segment type 1 transport model for Lake Baikal.

TABLE 7. CHARACTERISTICS OF FOURTEEN-SEGMENT TYPE 1 TRANSPORT MODEL FOR LAKE BAIKAL

Segment Number	N	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Surface Area	$S(km^2)$	1150	2950	2325	3150	2550	2050	2850	1175	1625	1725	1575	2200	1950	1850
Volume	$V(km^3)$	230	590	465	630	510	410	770	235	325	345	315	440	390	370

Inflow: Selenga 2.5 km^3/yr
Barguzin 1.063 km^3/yr
Upper Angara 1.5 km^3/yr

Outflow: Angara 5.063 km^3/yr

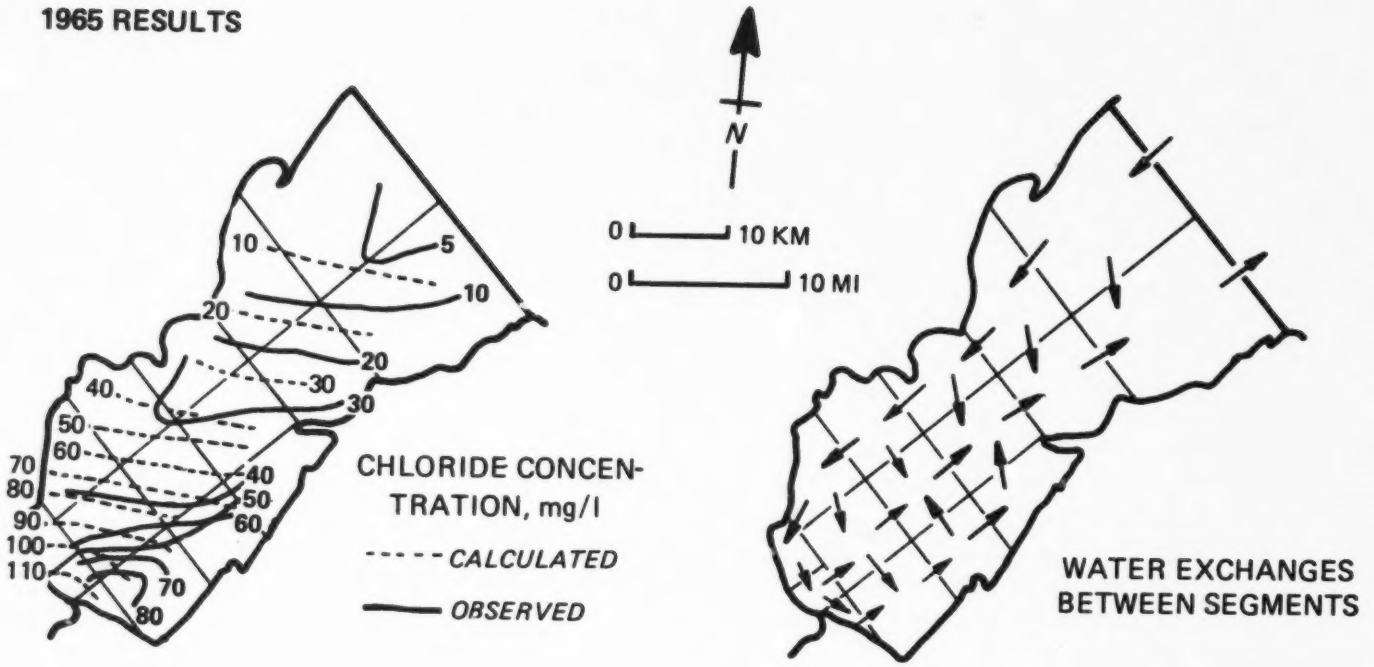


Figure 19. Sixteen-segment type 1 transport model for Saginaw Bay.

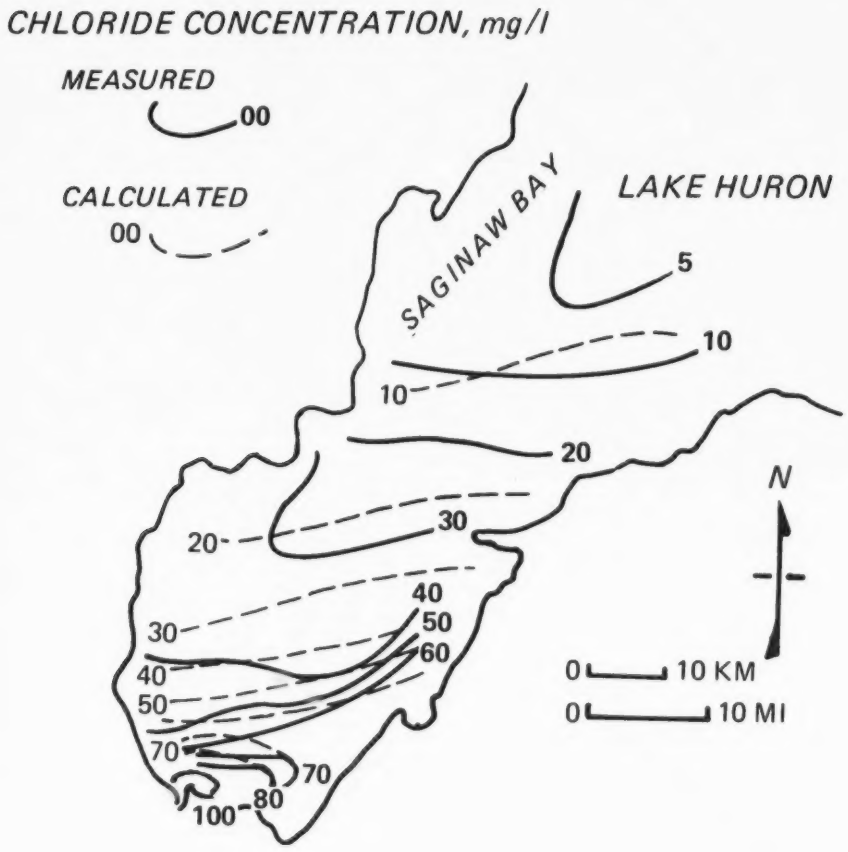


Figure 20. Type 2 transport model calibration with 1965 Saginaw Bay chloride concentrations.

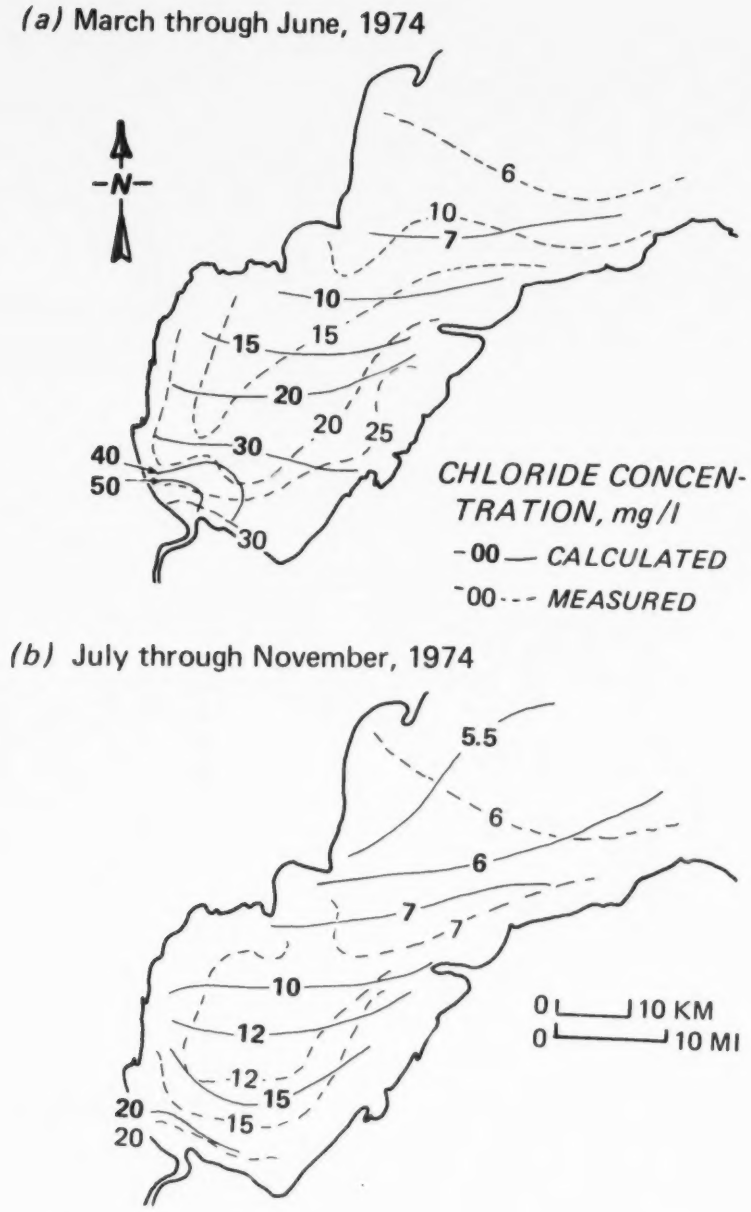


Figure 21. Type 2 transport model verification with 1974 Saginaw Bay chloride concentrations.

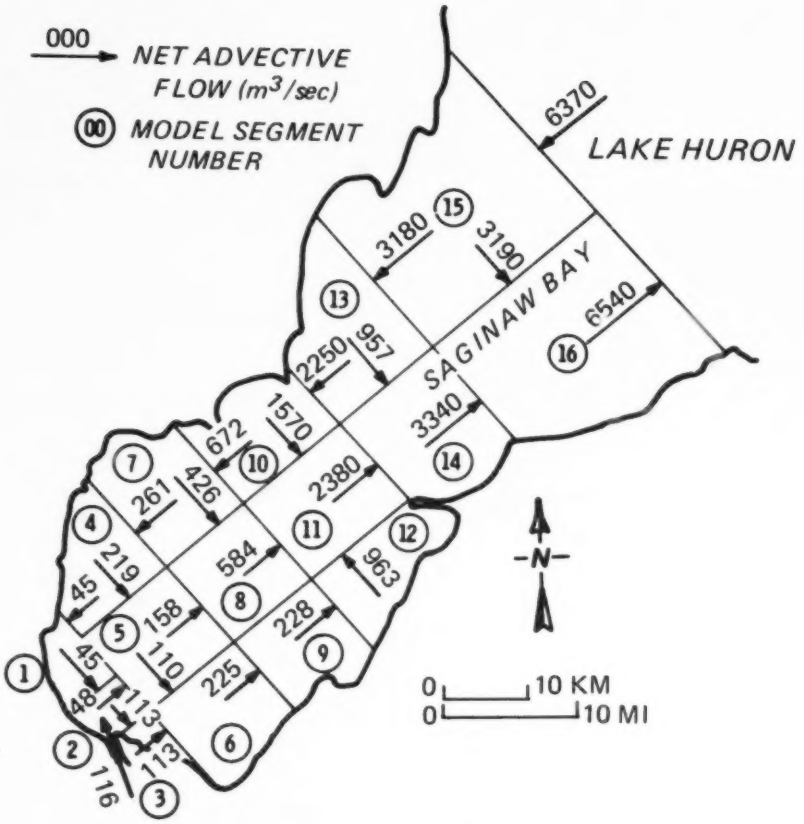


Figure 22. Type 2 transport model water exchanges for Saginaw Bay.

TABLE 8. PARAMETERS FOR SEA OF AZOV HYDRODYNAMIC MODEL

Grid spacings	6.84 km y-direction 9.46 km x-direction
Horizontal extents	362.5 km y-direction 217.5 km x-direction
Number of grid points	54 y-direction 24 x-direction 8 z-direction
Minimum depth	1 m
Maximum depth	13 m
Coriolis parameter (46°N)	1.046×10^{-4} /sec
Horizontal eddy viscosity	3×10^{6} cm^2/sec
Vertical eddy viscosity	25 cm^2/sec
Horizontal eddy diffusivity	3×10^{6} cm^2/sec
Vertical eddy diffusivity	10 cm^2/sec
Particle settling velocity	10 m/day

T = temperature (°C), and

S = salinity (gm/kg).

The Sea of Azov is generally mixed vertically because it is so shallow, and it is generally of uniform temperature during the summer (around 20°C). This value for the temperature was used in the equation-of-state. Figure 23 indicates the horizontal grid scheme used for the discretization process. Variable-density, uniform temperature calculations were performed to make comparisons with currents that were observed during the summer of 1957. These currents and winds were presented earlier in Figure 7. The data did not suggest what currents these were: surface currents, near-surface currents, vertically averaged currents, or vertically integrated currents. One additional calculation was performed using the basic wind from the second observed case for an increased Don River flow of 5 km^3/year. This corresponds to the amount of water that is considered for rediversion back into the river in an effort to reverse the trend of increasing salinity in the sea. It was hoped that the two calculations would indicate if the trend could be changed. Table 9 indicates the conditions specific to each of the calculations that were made. The basic data for inflows, outflows, evaporation, etc., are from Table 4. The flows in each direction through the straits between the Sea of Azov and the Black Sea were based on historical records (Semenov 1972). Typical flows for the summer were used, with flow from the Sea of Azov into the Black Sea in the surface portion of the straits and flow intrusion into the Sea of Azov through the deeper portion of the straits. The salinity of water flowing from the Black Sea was set at 17 gm/kg. One difficulty that did develop when applying the conditions to the model was in the detail of the wind field (e.g., Case 3 is considered essentially a constant westerly wind situation). However, it was found that a completely constant wind could not be used to calculate the current pattern suggested for this wind. Since existing data indicated that the wind is constant to within 7-10 m/sec, a wind pattern with variation over this range was tried in the calculation. Part of the calculation procedure with the model thus consisted of experimenting with different wind patterns, within the limits specified by the data, to determine what would best approximate the observed results.

Complete results of the calculations are presented in Appendix C. All of the calculations were performed for 2 days of real time with the wind and river flows constant over this time period. The initial conditions for the salinity distribution were obtained from the initial salinity values used in the transport model of Gorstko and Surkov for the sea (see next section). After 2 days, the currents achieved quasi-steady-state. The salinity distribution was still slowly varying in time, and thus affecting the current calculations, but these changes were small and had a negligible affect on the comparison with the observed data. The results for Case 3 of the observed data were obtained for both a spatially uniform wind, and for a slightly varying wind. It was observed that the calculated currents below the surface and the vertically integrated currents were significantly affected by the spatial variation of the wind. Sample results for the currents at 2 meters below the water surface are shown in Figure 24. These currents agree best with the observed data. The major discrepancies appear

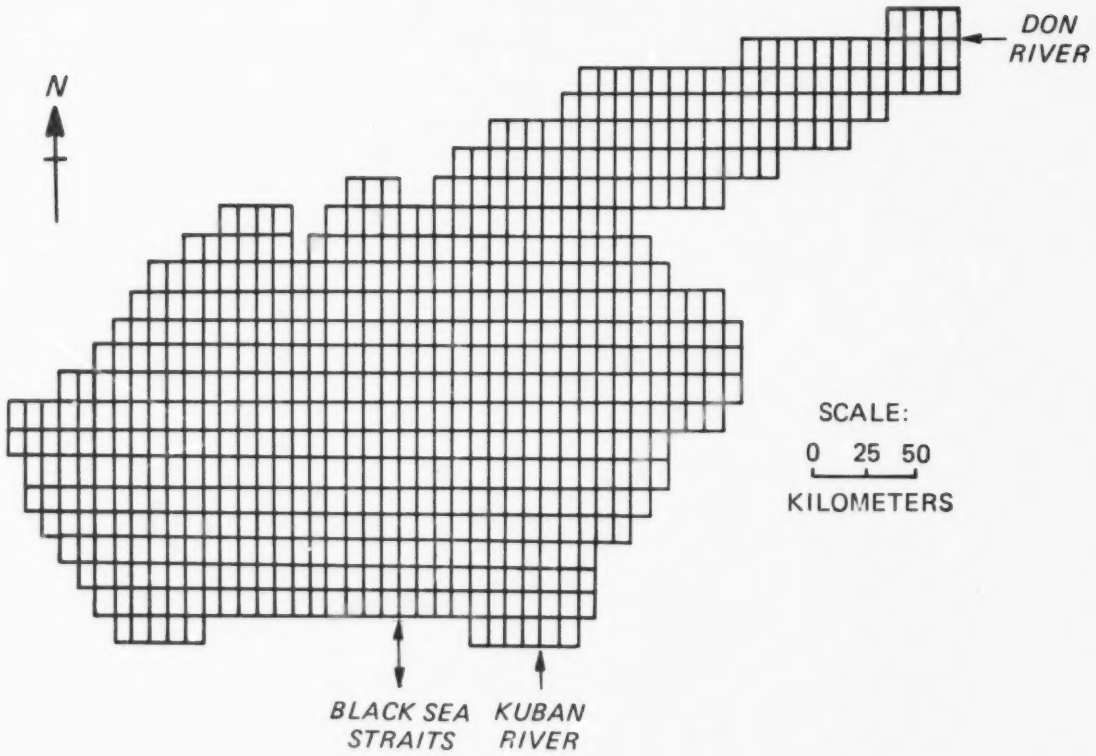


Figure 23. Hydrodynamic model grid for Sea of Azov calculation.

TABLE 9. PARAMETERS FOR THREE WIND CASES
OF SEA OF AZOV CALCULATIONS

		Case 1	Case 2	Case 2a	Case 3
Q_1 (Don)	m^3/sec	530	600	760	570
	cm^3/sec	5.3×10^8	6.0×10^8	7.6×10^8	5.7×10^8
Q_2 (Kuban)	m^3/sec	500	520	520	450
	cm^3/sec	5.0×10^8	5.2×10^8	5.2×10^8	4.5×10^8
Evaporation	mm/day	2.4	2.0	2.0	2.8
	cm^3/sec	10.4×10^8	8.7×10^8	8.7×10^8	12.2×10^8
Precipitation	mm/day	0	0	0	0.4
	cm^3/sec	0	0	0	1.8×10^8
Net flow out straits	cm^3/sec	$-.1 \times 10^8$	2.5×10^8	4.1×10^8	$-.2 \times 10^8$
Flow from Sea of Azov to Black Sea	cm^3/sec	7.7×10^8	8.4×10^8	9.6×10^8	7.7×10^8
Flow from Black Sea to Sea of Azov	cm^3/sec	7.8×10^8	5.9×10^8	5.5×10^8	7.9×10^8

in replicating the center of the gyre for all of the cases. Problems also appear in duplicating the currents for Case 1 south of the Tagonrog Bay area and along the southern shore of the sea. These problems may be due to the variations in the wind that probably occurred during the observations, but for which no information is available.

The results of the calculations to determine the effect of an increased flow in the Don River are shown in Figure 25 for the surface salinity distributions. These calculations are identical to the previous except that they represent 6 months of real time. A comparison does indicate that the increased river flow can change the salinity in the sea. The results indicate an average drop of .1 gm/kg in salinity for the sea over the time period of increased river flow. It should be remembered that these calculations are for a somewhat arbitrary flow through the straits. The results are sensitive to the conditions specified at the straits, and a different change in average salinity could be obtained for different conditions. The flow conditions used were typical of the summer when the Black Sea flow into the Sea of Azov was maximal.

The transport and dispersion of material in the sea were made using the currents calculated for Cases 1 and 3. For each case, two different calculations were performed: one for neutrally buoyant particles, and one for particles with gravitational settling velocities of 10 m/day. The first corresponds to dissolved materials, and the second to suspended solids. The calculations were performed for 28 days with material continually added through the Kuban and Don Rivers. The material concentration in the rivers was arbitrarily set to 1.0. Since the equations to be solved are linear, the actual concentration values are not important. The results of the calculations are presented in Appendix C. Figure 26 shows the surface and bottom concentrations with the Case 1 calculated currents for both dissolved and suspended material. The calculation for the suspended material is not significantly different than the dissolved material calculation. This may seem odd since the same settling velocity was used in the Lake Baikal transport calculation and the results there were decidedly different. This is explained when the relative importance of vertical mixing and gravitational settling for these two applications is examined. This is indicated by a vertical Reynolds number based upon the settling velocity, i.e., $w_s h/D_V$, where w_s is the settling velocity, h is the depth and D_V is the vertical turbulent diffusivity. For the Sea of Azov calculation, this number is approximately 1, while for the Lake Baikal calculation, this number ranges from 10 to 100. So, the gravitatinal settling is significantly more important than vertical mixing for the Lake Baikal calculation, while for the Sea of Azov calculation, both are of equal importance. This behavior is typical of shallow seas and lakes, that is, suspended solids remain in the water column for long periods of time. The flux out of the water column is determined by the bottom boundary condition. This detail has not been addressed in this study. Another observation of the results for the dispersion calculation is that materials added from the Kuban River disperse throughout the sea much more rapidly than materials added from the Don River. This is mainly due to the reduced flow occurring in Tagonrog Bay. Material input from the Don River has to be transported through this bay

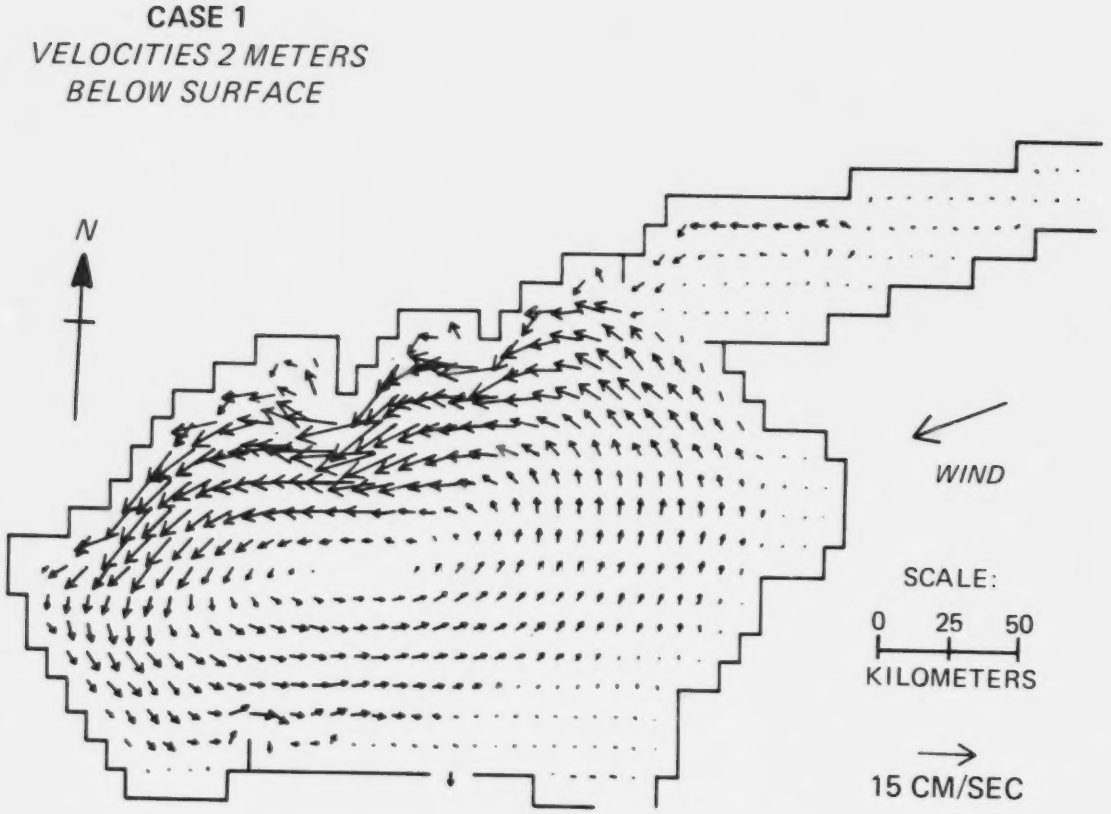


Figure 24a. Hydrodynamic model calculation for Sea of Azov.

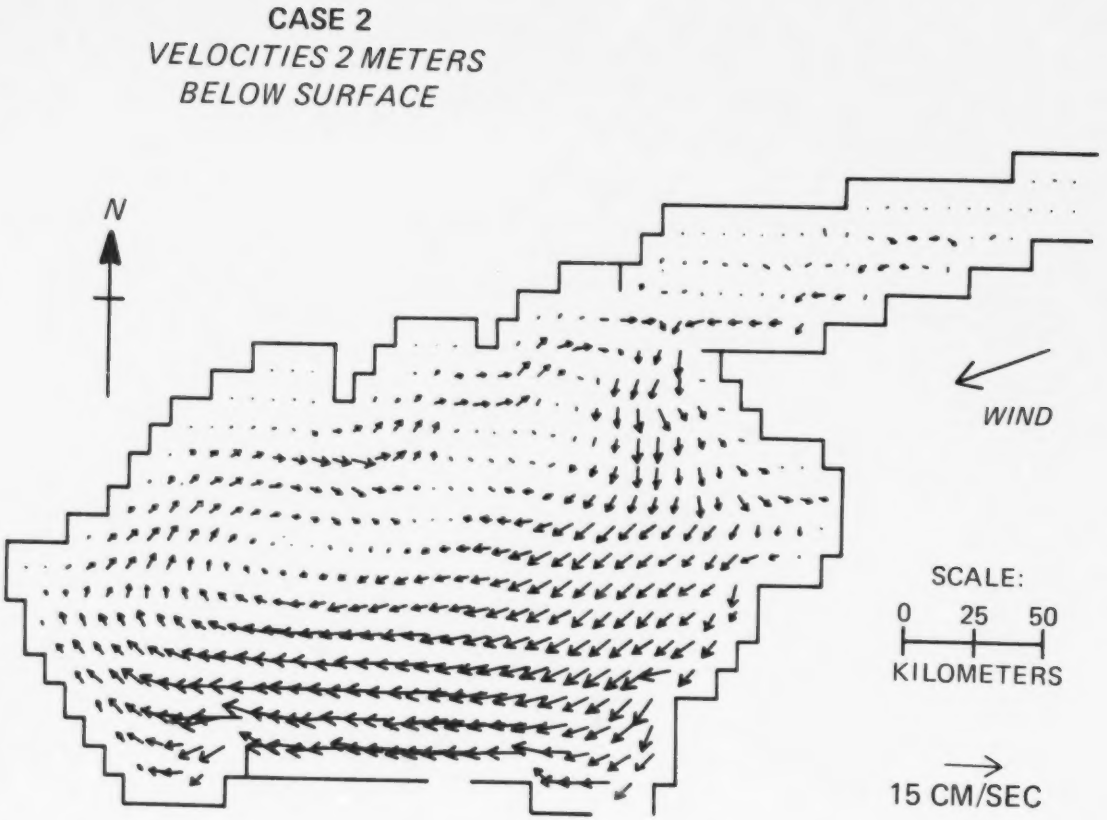


Figure 24b. Hydrodynamic model calculation for Sea of Azov.

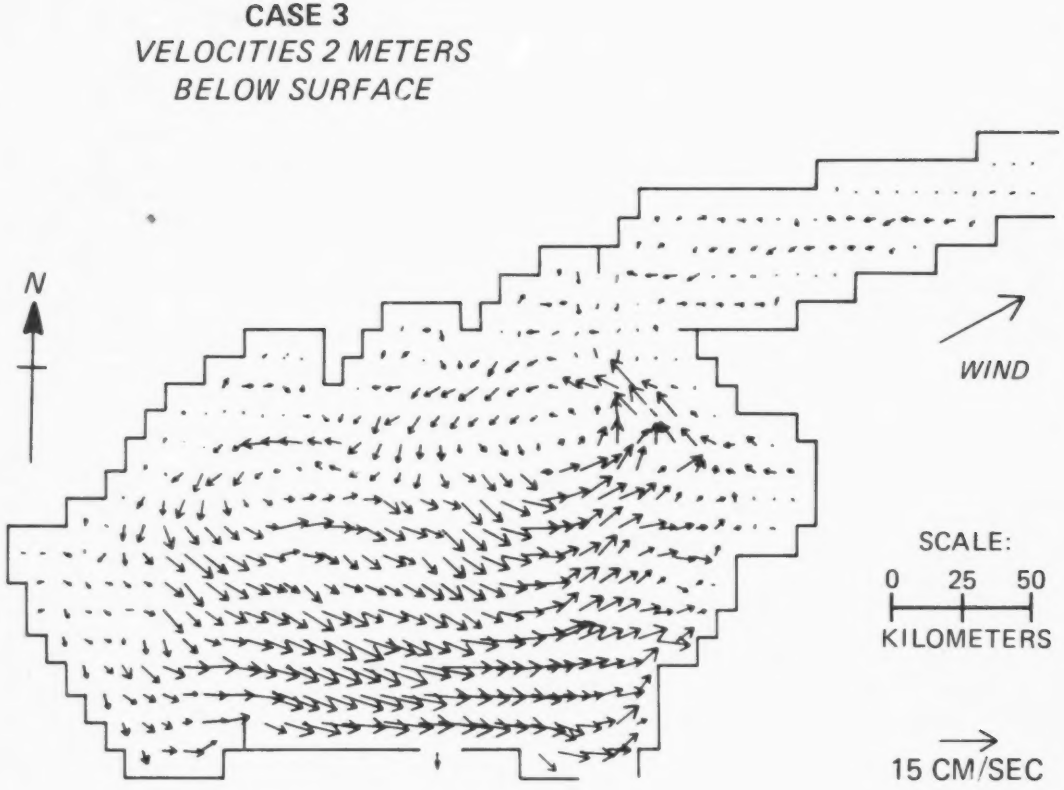


Figure 24c. Hydrodynamic model calculation for Sea of Azov.

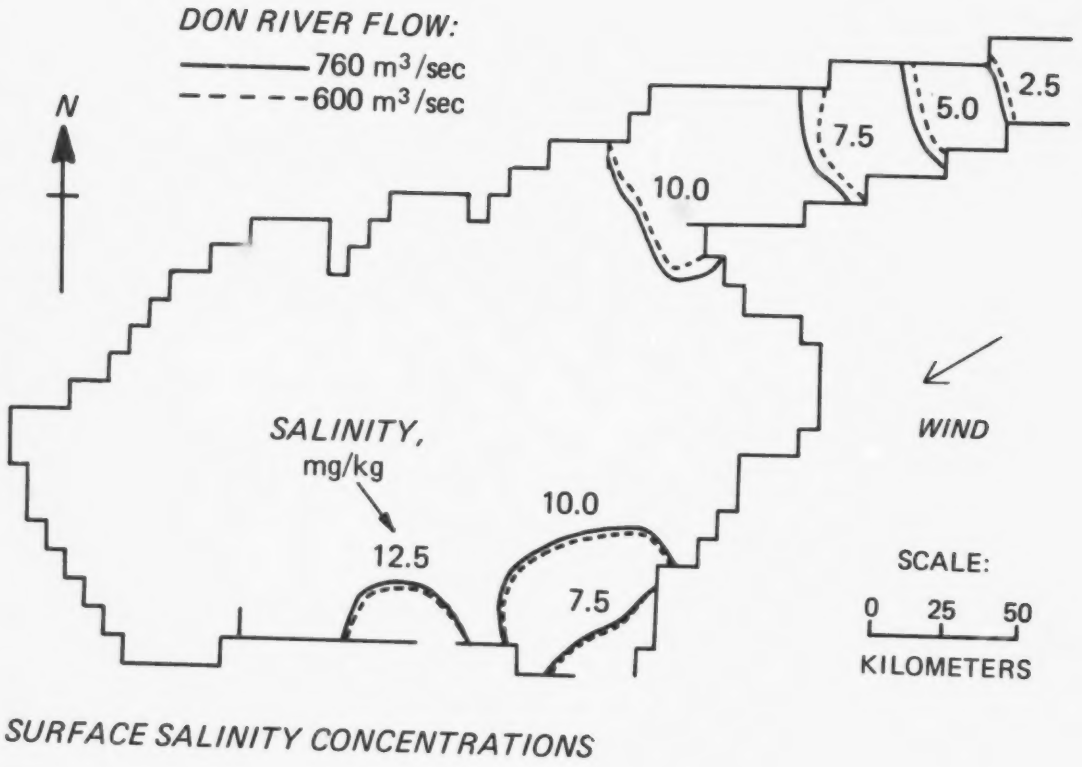


Figure 25. Surface salinity in Sea of Azov after six months with and without increased Don River flow.

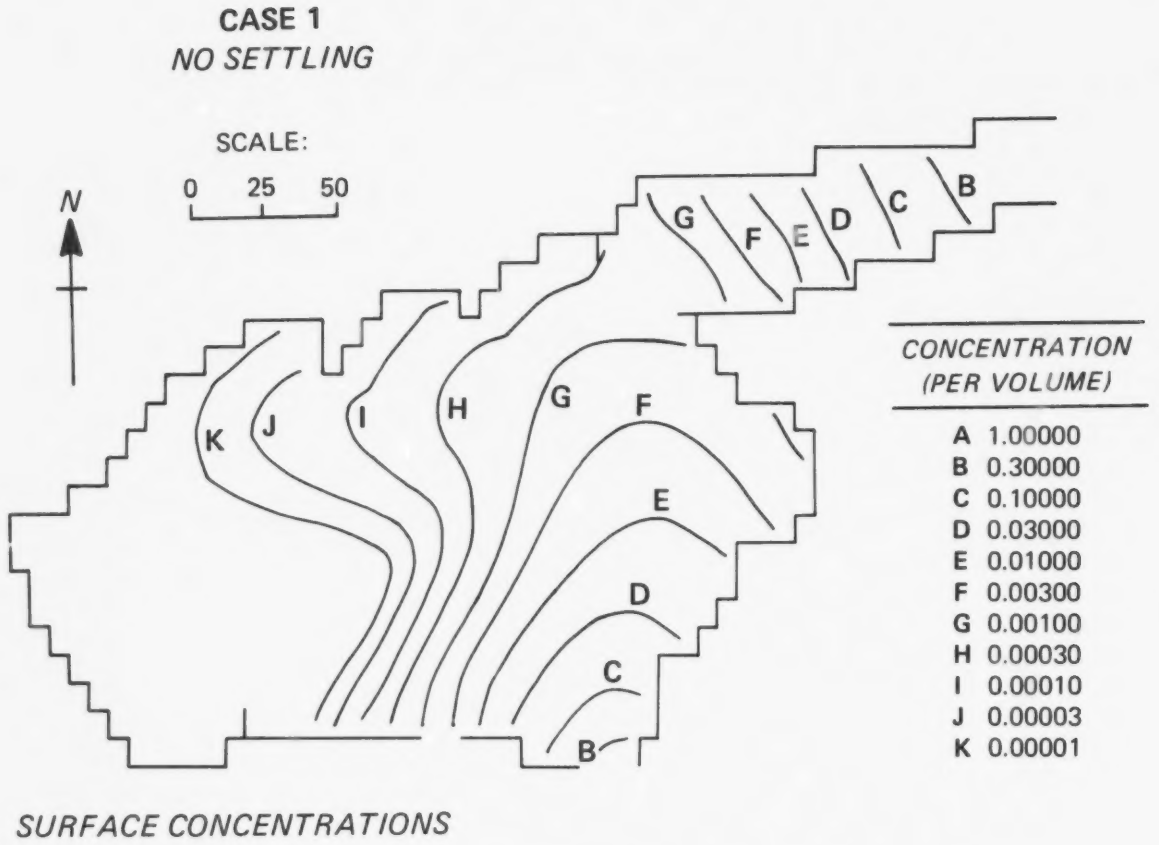


Figure 26a. Dispersion model calculation for Sea of Azov.

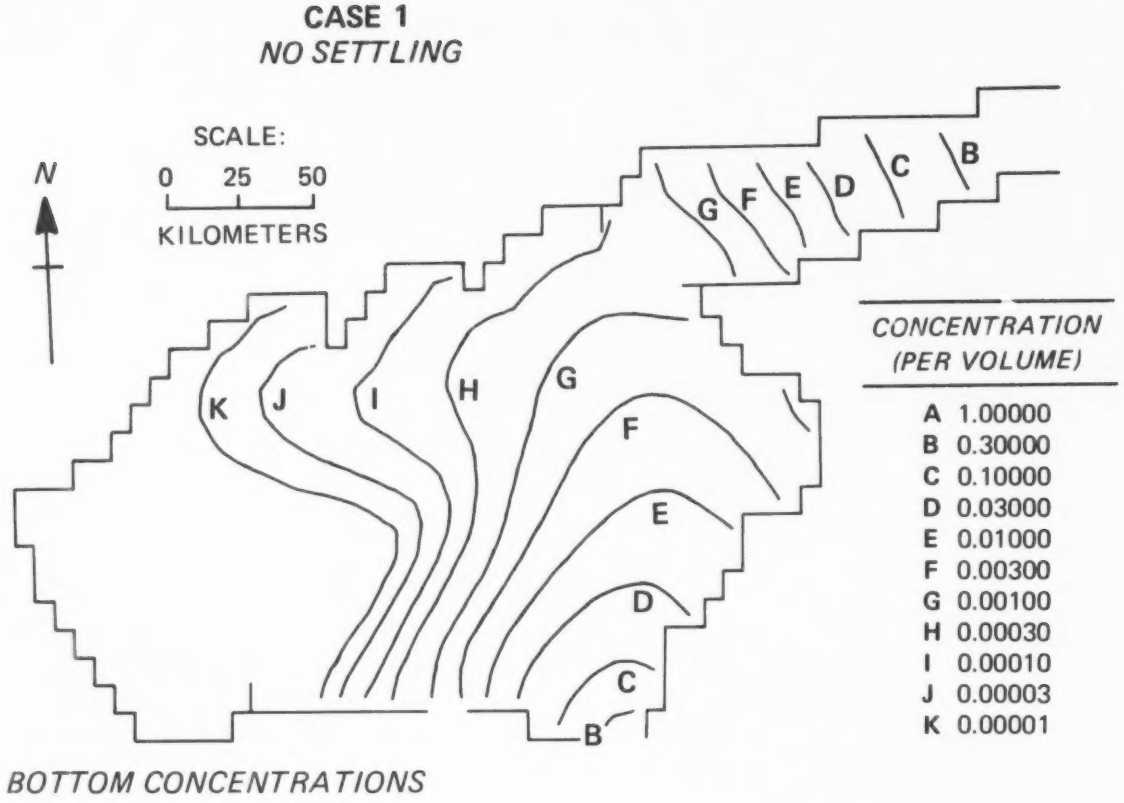


Figure 26b. Dispersion model calculation for Sea of Azov.

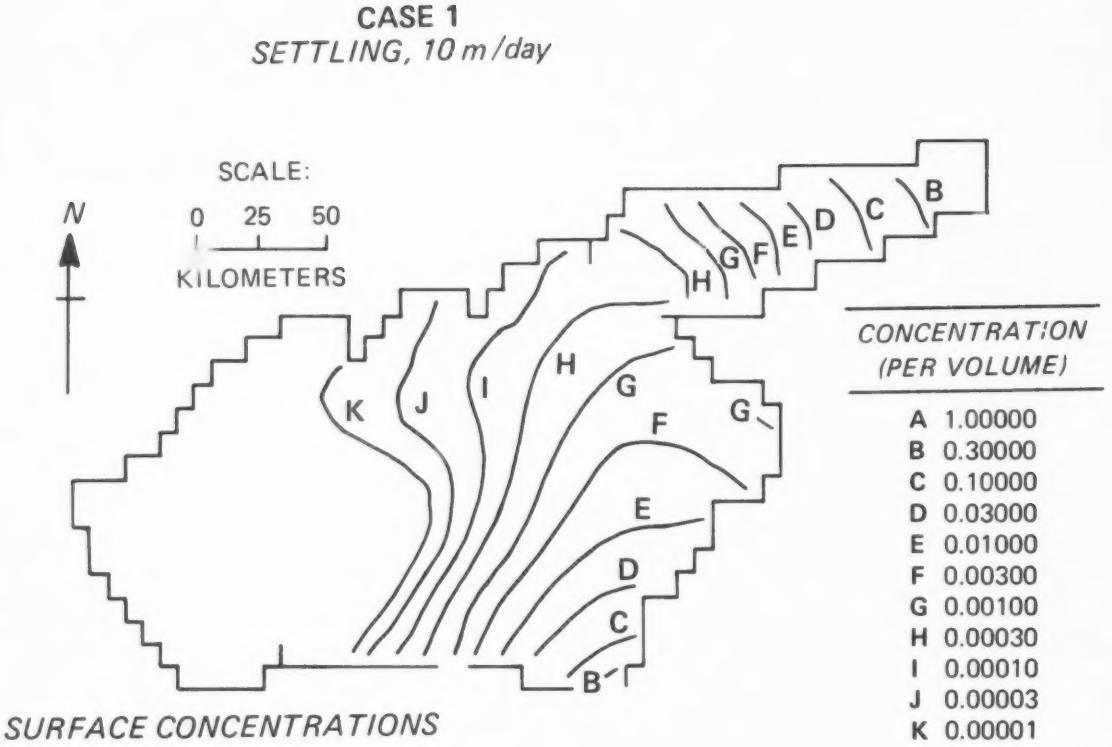


Figure 26c. Dispersion model calculation for Sea of Azov.

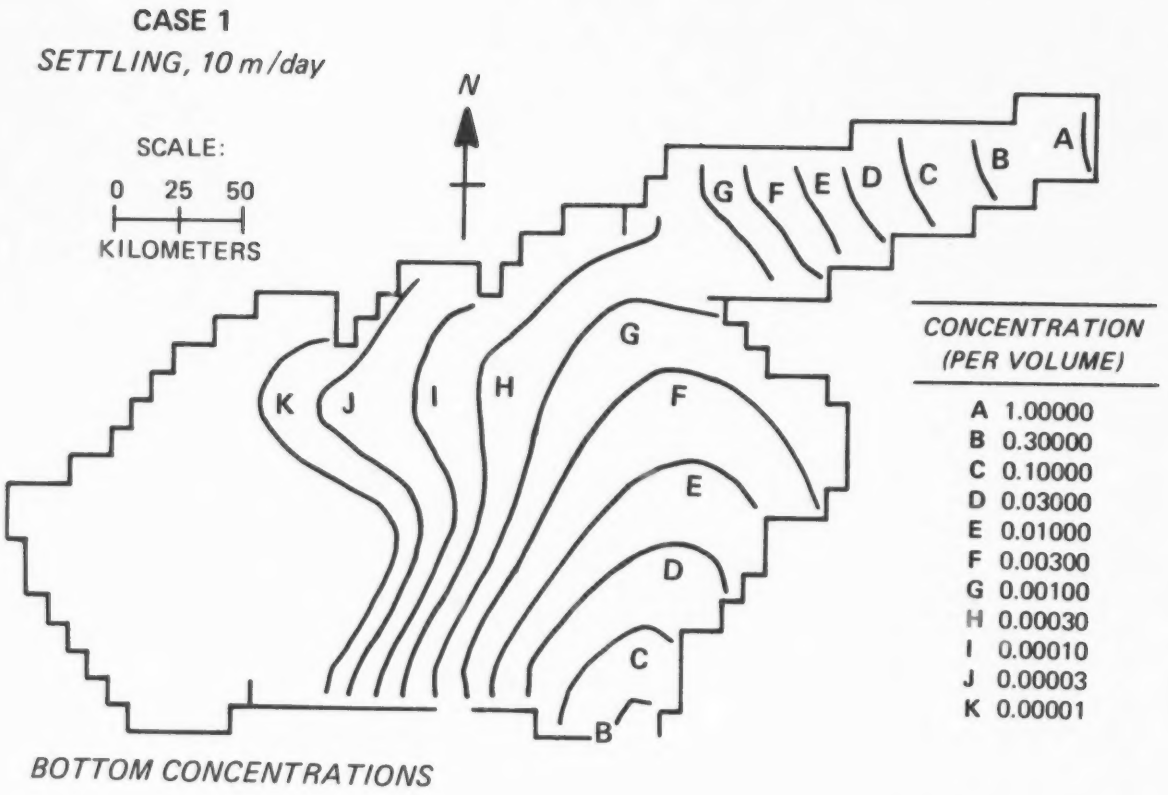


Figure 26d. Dispersion model calculation for Sea of Azov.

before it enters the main portion of the sea, while the Kuban River empties almost directly into the main portion of the sea. No data were available for this study to compare with the dispersion calculations.

Type 1 Transport Calculation

The type 1 steady-state transport model developed by Gorstko and Surkov (1975) was applied to a 7-segment model for the Sea of Azov. The model was applied to the 3 cases observed during the summer of 1957 (Figure 7 and Table 4). The water exchanges determined for the 3 cases are shown in Figure 27. These agree with the observed currents (Figure 7). The transient transport model was applied to salinity dynamics using the water exchanges determined for Case 2. Table 10 indicates the initial salinity values, and the values calculated 5 days later. The calculated results agree within one percent with the observed values.

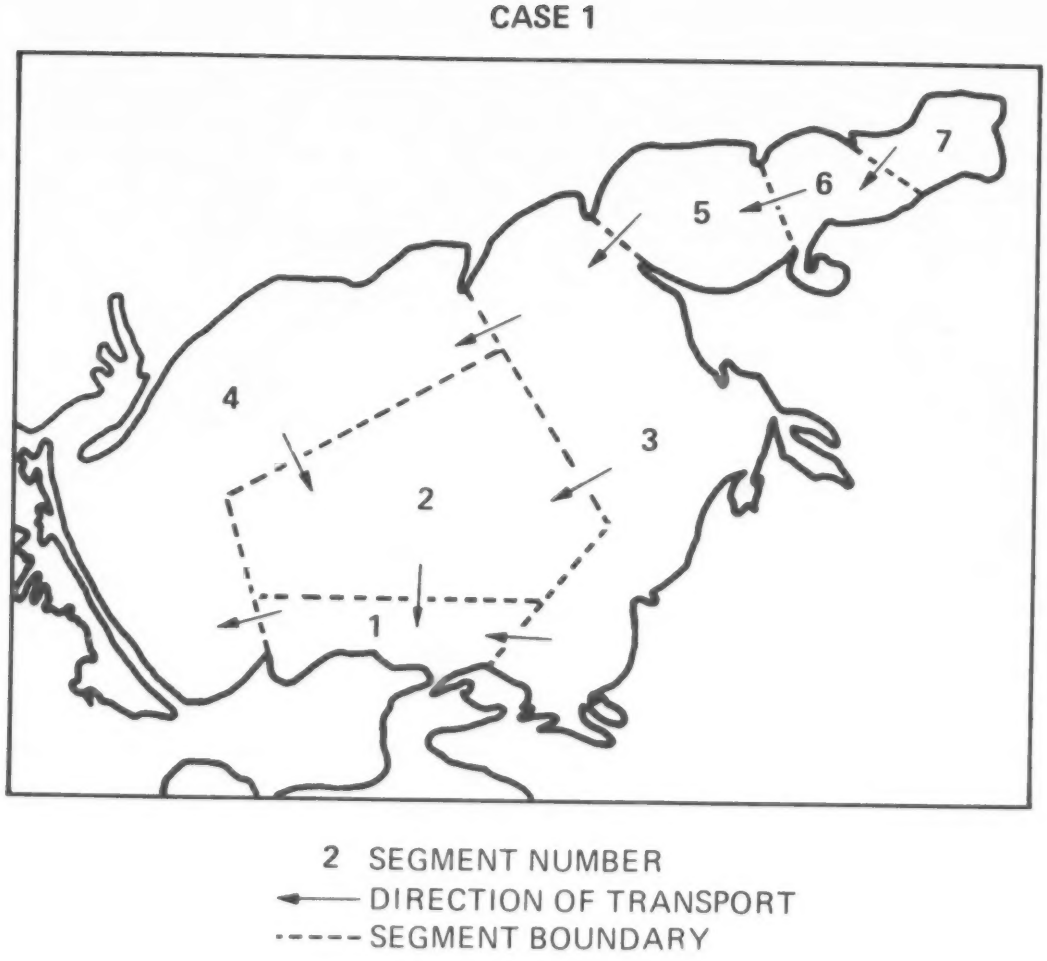


Figure 27a. Type 1 transport model calculation for Sea of Azov.

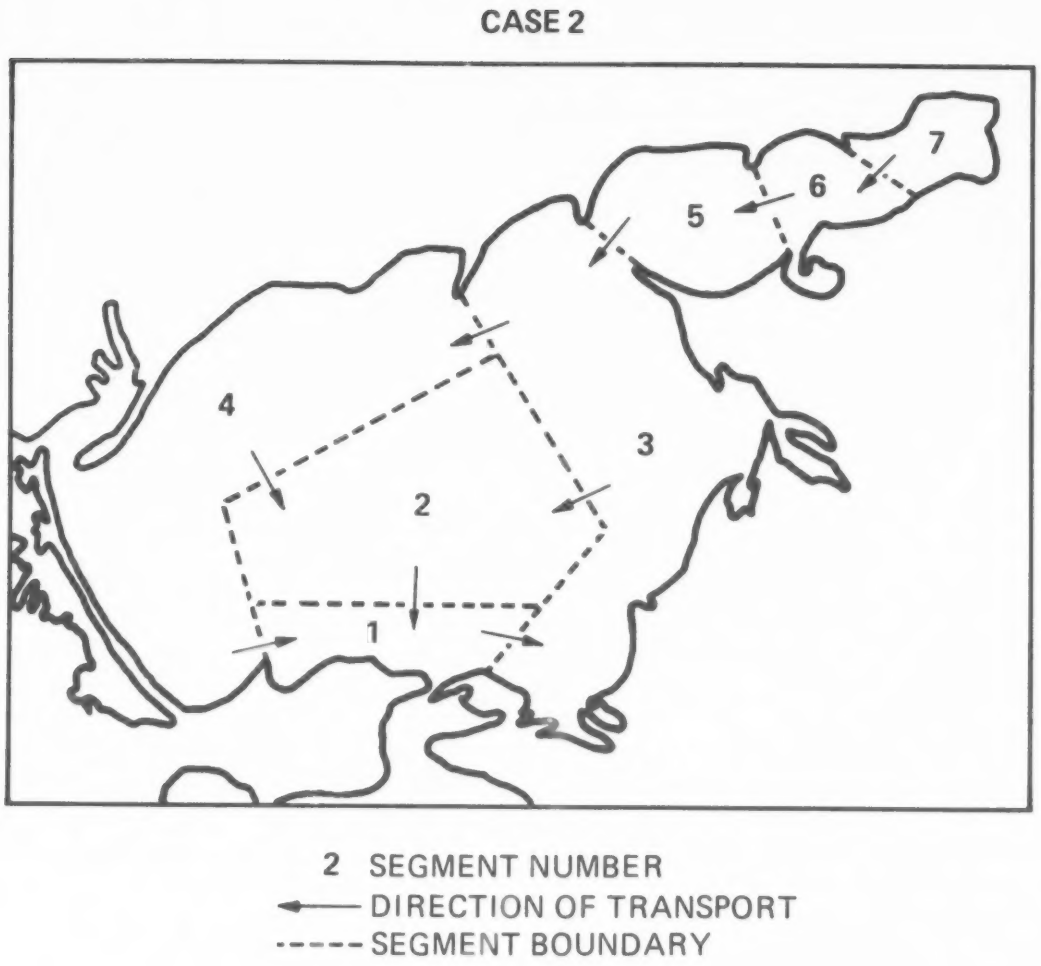


Figure 27b. Type 1 transport model calculation for Sea of Azov.

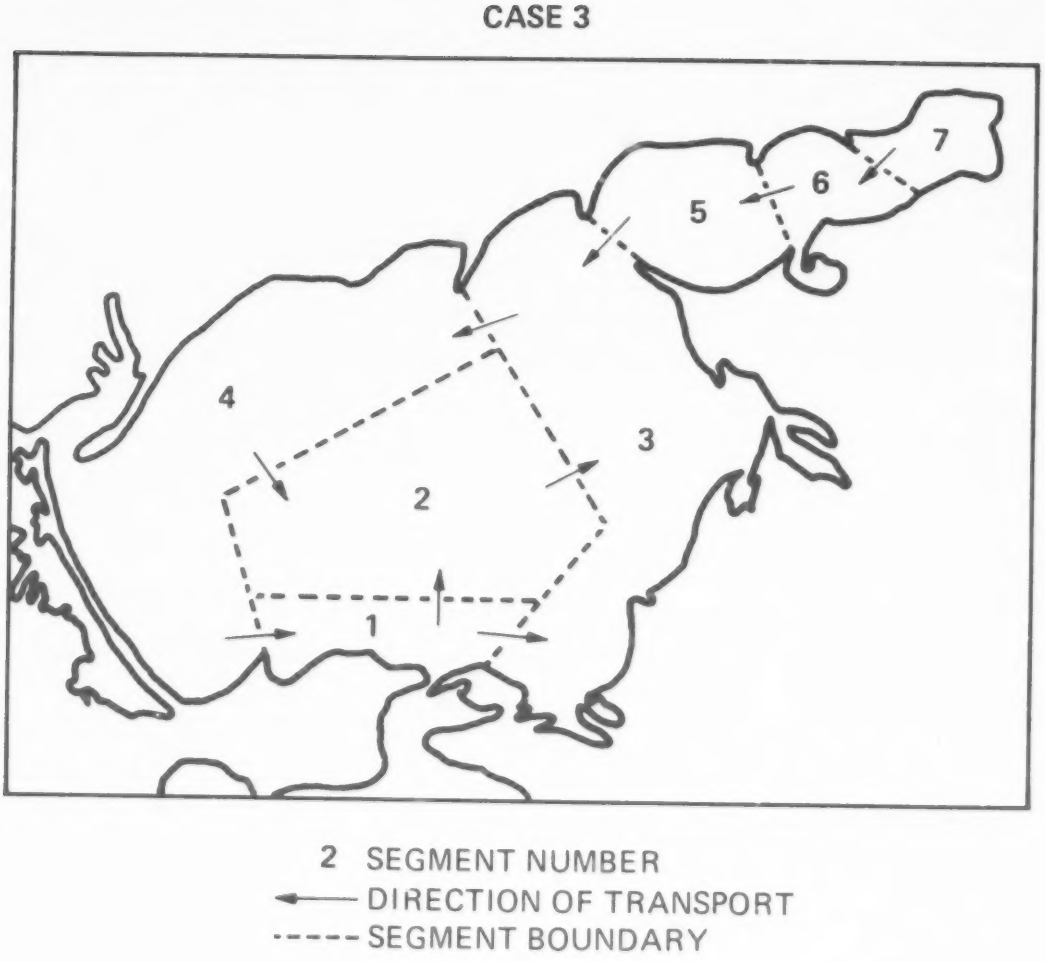


Figure 27c. Type 1 transport model calculation for Sea of Azov.

TABLE 10. TYPE 1 TRANSPORT MODEL SALINITY FOR SEA OF AZOV

Segment	Initial salinity (gm/kg)	Calculated salinity after 5 days (gm/kg)
1	10.761	10.736
2	10.641	10.620
3	9.884	9.846
4	10.686	10.667
5	6.915	6.796
6	3.940	3.787
7	1.451	1.382

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APPENDIX A

AGREEMENT ON COOPERATION IN THE FIELD OF ENVIRONMENTAL PROTECTION BETWEEN THE UNITED STATES OF AMERICA AND THE UNION OF SOVIET SOCIALIST REPUBLICS

The Government of the United States of America and the Government of the Union of Soviet Socialist Republics:

Attaching great importance to the problems of environmental protection;

Proceeding on the assumption that the proper utilization of contemporary scientific, technical and manageable achievements can, with appropriate control of their undesirable consequences, make possible the improvement of the interrelationship between man and nature;

Considering that the development of mutual cooperation in the field of environmental protection, taking into account the experience of countries with different social and economic systems, will be beneficial to the United States of America and the Union of Soviet Socialist Republics, as well as to other countries;

Considering that economic and social development for the benefit of future generations requires the protection and enhancement of the human environment today;

Desiring to facilitate the establishment of closer and long-term cooperation between interested organizations of the two countries in this field;

In accordance with the Agreement between the United States of America and the Union of Soviet Socialist Republics on Exchanges and Cooperation in Scientific, Technical, Educational, Cultural, and Other Fields in 1972-1973, signed April 11, 1972, and developing further the principles of mutually beneficial cooperation between the two countries;

Have agreed as follows:

Article 1

The Parties will develop cooperation in the field of environmental protection on the basis of equality, reciprocity, and mutual benefit.

Article 2

This cooperation will be aimed at achieving the most important aspects of the problems of the environment and will be devoted to working out measures to prevent pollution, to study pollution and its effect on the environment, and to develop the basis for controlling the impact of human activities on nature.

It will be implemented, in particular, in the following areas:

Air pollution;
Water pollution;
Environmental pollution associated with agricultural production;
Enhancement of the urban environment;
Preservation of nature and the organization of preserves;
Marine pollution;
Biological and genetic consequences of environmental pollution;
Influence of environmental changes on climate;
Earthquake prediction;
Arctic and subarctic ecological systems;
Legal and administrative measure for protecting environmental quality.

In the course of this cooperation the Parties will devote special attention to joint efforts improving existing technologies and developing new technologies which do not pollute the environment, to the introduction of these new technologies into everyday use, and to the study of their economic aspects.

The Parties declare that, upon mutual agreement, they will share the results of such cooperation with other countries.

Article 3

The Parties will conduct cooperative activities in the field of environment protection by the following means:

Exchange of scientists, experts and research scholars;
Organization of bilateral conferences, symposia and meetings of experts;
Exchange of scientific and technical information and documentation, and the results of research on environment;

Joint development and implementation of programs and projects in the field of basic and applied sciences;
Other forms of cooperation which may be agreed upon in the course of the implementation of this Agreement.

Article 4

Proceeding from the aims of this Agreement the Parties will encourage and facilitate, as appropriate, the establishment and development of direct contacts and cooperation between institutions and organizations, governmental, public and private, of the two countries, and the conclusion, where appropriate, of separate agreements and contracts.

Article 5

For the implementation of this Agreement a US-USSR Joint Committee on Cooperation in the Field of Environmental Protection shall be established. As a rule this Joint Committee shall meet once a year in Washington and Moscow, alternately. The Joint Committee shall approve concrete measures and programs of cooperation, designate the participating organizations responsible for the realization of these programs and make recommendations, as appropriate, to the two Governments.

Each Party shall designate a coordinator. These coordinators, between sessions of the Joint Committee, shall maintain contact between the United States and Soviet parts, supervise the implementation of the pertinent cooperative programs, specify the individual sections of these programs and coordinate the activities of organizations participating in environmental cooperation in accordance with this Agreement.

Article 6

Nothing in this Agreement shall be construed to prejudice other agreements concluded between the two Parties.

Article 7

This agreement shall enter into force upon signature and shall remain in force for five years after which it will be extended for successive five year periods unless one Party notifies the other of the termination thereof not less than six months prior to its expiration.

The termination of this Agreement shall not affect the validity of agreement and contracts between interested institution and organizations of the two countries concluded on the basis of this Agreement.

DONE on May 23, 1972 at Moscow in duplicate, in the English and Russian languages, both texts being equally authentic.

FOR THE UNITED STATES OF AMERICA:

Richard Nixon

President of the United States of America

FOR THE UNION OF SOVIET SOCIALIST REPUBLICS:

N. V. N.V. Podgorny

Chairman of the Presidium of the Supreme Soviet of the U.S.S.R.